Sonoflex: Embroidered Speakers Without Permanent Magnets

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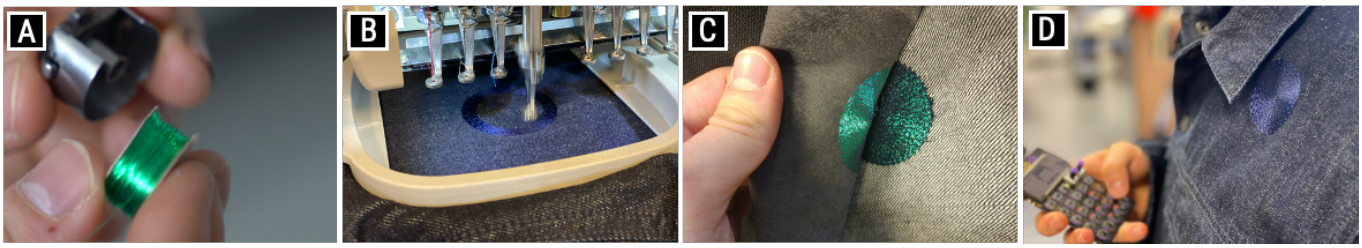

Figure 1. We propose a flexible embroidered speaker, which does not require a permanent magnet. By using a 0,15 mm Cu/Ag20 yarn (A), we embroider two flat coils (B) which are placed on top of each other (C). One possible demo application could be an embroidered jacket speaker which can be controlled with a pocket synthesizer (D).

ABSTRACT
We present Sonoflex, a thin-form, embroidered dynamic speaker made without using a permanent magnet. Our design consists of two flat spiral coils, stacked on top of each other, and is based on an isolated, thin (0.15 mm) enameled copper wire. Our approach allows for thin, lightweight, and textile speakers and does not require high voltage as in electrostatic speakers. We show how the speaker can be designed and fabricated and evaluate its acoustic properties as a function of manufacturing parameters (size, turn counts, turn spacing, and substrate materials). The experiment results revealed that we can produce audible sound with a broad frequency range (1.5 kHz - 20 kHz) with the embroidered speaker with a diameter of 50 mm. We conclude the paper by presenting several applications such as audible notifications and near-ultrasound communication.

Author Keywords
Embroidery, embroidered speaker, lightweight speaker, smart textile, textile loudspeaker, textile transducer.

INTRODUCTION
Textile based input and output interfaces allow for seamless integration of technology into our everyday environments. Consequently, there have been numerous efforts in wearable computing research over the last decades specifically focusing on interactive textiles [33, 42, 36]. As electronic components are becoming more compact, flexible, and efficient at the same time, evidently, both academic and maker communities as well as artists embrace new potentials in augmenting existing textiles with diverse input modalities [39, 16, 55, 25, 38, 4, 17]. Also, a large body of work is committed to using e-textiles as output medium, be it visual [26], auditory [27] or for actuation [6, 1].

In this paper, we present Sonoflex, a design for a textile-based, embroidered speaker (see Figure 1), capable of lo-fi audible as well as near-ultrasound output *without* requiring a permanent magnet (C). We focus on the design and fabrication aspects of our implementation using flat air-core coils (B), made of enameled wire (A). As a consequence, we greatly reduce the device's weight and rigidity, as well as fabrication complexity, while keeping it harmless to the wearer by using low operating voltages, when compared to flexible electrostatic speakers (D).

We first introduce and discuss the basic concept of our embroidered speaker and show several options for implementation. Subsequently, we present a range of speaker prototypes, varying geometric and fabrication parameters (e.g. coil size, turn count, turn spacing, fabric substrate), which were evaluated in order to maximize performance.

Our results show that we are able to emit audible sound with a broad frequency range (1.5 kHz - 20 kHz) with a mean value of 29.34 dB $\pm$ 4.88 dB SPL, using a coil diameter of 50 mm. Furthermore, we present a set of application scenarios arising from our speaker design, including a beanie notifier, a jacket speaker that is fed with music from a handheld synthesizer, as well as close-range data communication. Finally, we conclude with discussion, limitations, and future work.

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In summary, the contributions of this paper are:

- We demonstrate a textile-based embroidered speaker, which is operational *without* permanent magnets and potentially dangerous high voltages.
- Details on the functionality and lessons learned regarding design and fabrication.
- Insights with respect to relevant design and fabrication parameters, including results of our experiments.
- Finally, we present a set of applications and discuss both advantages and limitations of our approach.

RELATED WORK

Our work relates to many areas of HCI research, including embroidered smart textiles, coils in textiles, and light-weight speakers. In this section, we address relevant work of each field, starting with a review of smart textiles, mostly focusing on embroidery. We then discuss work concerned with the implementation of textile coils. Finally, we discuss light-weight speakers and contrast them to Sonoflex.

Embroidered smart textiles

Due to the properties of textiles being lightweight, highly flexible, and often also stretchable they are applied in a wide range of use cases, e.g. for wireless monitoring suits [3], music control [7], multi-touch input [49, 15] and motion capturing systems [54, 11]. Machine embroidery has been one of the first fabrication techniques used in the field of smart textiles [37, 41], as it is highly useful for rapid prototyping [28, 48]. Mecnika et al. provide an excellent overview of numerous embroidered smart textile applications [31], including embroidered circuits, electroconductive interconnections, embroidered antennas, embroidered heating, and embroidered keypads. With Tessutivo [14], Gong et al. demonstrate an inductive sensing device based on embroidered textiles, which inspired our coil parameters and shapes, as well as the usage of different fabric substrates for evaluation.

Coils in textiles

Researchers use coils in combination with textiles for vastly different applications, ranging from inductive sensors for heart rate monitoring [24] to magnetic resonance sensors [34], furthermore for wireless charging of wearable electronics [50], and for inductive wireless power transfer [51, 29, 56]. In contrast to the mentioned applications, a higher turn count is necessary to implement an electromagnetic coil for a speaker, as the strength of the electromagnetic field is crucial.

Light-weight speakers

When implementing light-weight speakers many researchers focus on "paper-based" solutions Ishiguro et al. presented Uminari, an interactive electrostatic loudspeaker [19], which was also combined with 3D printed objects [20]. Similarly, Kato et al. presented OrigamiSpeaker, a hand-crafted paper electrostatic speaker, which is low-cost and can easily be fabricated with inkjet-printers [23]. Beyond electrostatic loudspeakers, researchers implemented a piezoelectric version of a paper-speaker [18].

A variety of textile speakers has already been built by researchers and artists. A starting point for our research was the work of the Kobakant collective [47, 40] and Leclerc and Berzowska from the XS Labs [27]. They used a textile as base for an embroidered coil as well as the speakers diaphragm. In contrast to our approach, they utilized permanent magnets fixed to the speaker for an opposing magnetic field.

The main inspiration for our work is drawn from Dinh [5], who presented a concept of a speaker lacking a permanent magnet which is based on two coils. Their main objective was implementing a lightweight speaker. While the concept and motivation are similar, our solution uses flat air-core coils fixed onto textiles which act as a diaphragm, omitting a heavy ferromagnetic core and consequently further reducing weight.

SPEAKER DESIGN

Essentially, a loudspeaker generates sound by pushing air via a moving membrane. In a dynamic speaker, which is the most common type, an electromagnet (also called voice coil) is mounted onto the membrane, which interacts with the magnetic field of a fixated permanent magnet. The voice coil is fed with the audio signal, which causes corresponding repelling and attracting forces, ultimately moving the membrane in correspondence to the signal's amplitude. In contrast, as we are dealing with textiles and inherently are bound to surfaces, we make use of two flat spiral coils, mutually attracting and repelling, thus simultaneously acting as our speaker's membranes (see Figure 2).

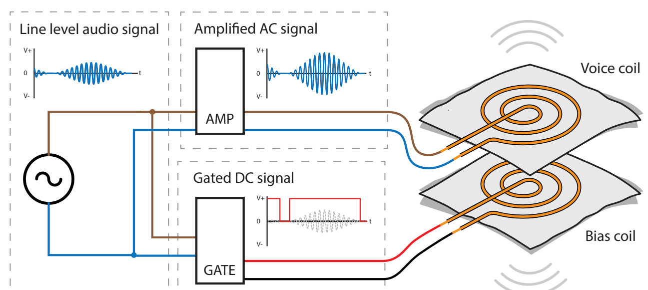

Figure 2. The function principle of the embroidered speaker. The voice coil is powered by the amplified source signal, the bias coil is powered by a gated DC signal. A full-wave rectifier with a smoothing capacitor was used in our implementation to power the bias coil.

Flat air-core coils are widespread in PCBs design, although generally with a comparable low turn count. While they are usually meant for inductive sensing, we want to generate adequate magnetic flux density and resulting Lorentz Forces to cause sufficient physical motion of our speaker membranes. Furthermore, we are trying to maximize pressure, thus force by area, to achieve the highest performance in terms of sound pressure level. Consequently, our objective is to maximize the magnetic flux density, with a given length of wire or conductive yarn. From a coil-shaped as an Archimedean spiral C with $r(\phi) = \frac{a}{2\pi}\phi$, the magnetic flux density B on a point x can be derived from the Biot-Savart law as

$$B(x) = \frac{\mu_0 I}{4\pi} \oint_C \frac{x' \times \delta l}{|x'|^3},$$

where I is the current flowing through the coil, μ_0 is the magnetic constant, δl is an infinitesimal segment of C as a vector on curve position l with the direction along the flow of I, and x' is the distance vector from x to l. Since our speaker is composed of two identical coils, sandwiched coplanar and centered, we can estimate mutual Lorentz forces, resulting from opposing magnetic flux densities. According to the Ampere's force law, the Lorentz force exerted on a coil C_2, as resulting from the magnetic flux density B_1 of a coil C_1 is

$$F_1 = \frac{\mu_0 I_1 I_2}{4\pi} \oint_{C_2} \oint_{C_1} \frac{\delta l_1 \times (\hat{x}' \times \delta l_1)}{|x'|^3}$$

and vice versa for F_2 acting on C_1, where $\hat{x}'$ denotes the normalized vector of x'. Assuming identical coils, both forces are equal in magnitude and opposed in direction. Consequently, with mentioned simplifications, we can approximate the absolute value of the total force between C_1 and C_2 as

$$|F_{total}| \approx \frac{\mu_0 I^2}{2\pi} |F|$$

with $F = F_1 = -F_2$. When assuming identical current magnitudes $I = |I_1| = |I_2|$, we see that F_{total} scales proportionally to I^2. From that, it is apparent that we can make maximum use of both coils, when we power both coils with our input signal. However, according to the Ampere's force law, currents I_1 and I_2 are then always equidirectional, producing magnetic flux with equal directions, and consequently Lorentz forces in same directions with magnitudes depending on the input signal, thus the coils would be always attracting themselves but never repulse. Furthermore, this implies a doubling of output frequency, since during a single sine wave period, the membranes would attract (or repulse) twice instead of attracting and then repulsing. Hence, we need to rectify the input signal of the bias coil, so force vectors go both ways. Initially, we implemented a full wave bridge rectifier to produce the desired output [53]. The required gated DC signal can also be achieved with different approaches, e.g. with an envelope follower or a digitally controlled high-current transistor.

Coil shape

In related literature, non-circular shapes can be found, including squares, octagons, hexagons, among others [35, 52, 14]. Use cases are numerous, ranging from inductive sensors to oscillators. As mentioned earlier, our objective is to maximize the magnetic field and inherently, we require to maximize the number of turns of the resulting coil, which can be formulated as maximizing the shape outline's roundness

$$R = 4\pi \frac{A}{P}$$

where P is the shape outline length (i.e. perimeter) and A is the enclosed area, which for circular shapes needs to be approximated, as we are tackling spirals, we do not constitute closed shapes. R is maximized for circular outlines, which we deem our justification to focus on those.

IMPLEMENTATION

Conductive wire

Instead of using conductive yarns to embroider coils, as presented by Gong et al. [14], in Sonoflex, we use thin and insulated copper wires, enabling us to stitch dense coils. A special requirement to the wire is that it has to be usable with embroidery, thus it needs to be flexible and tear-resistant, while featuring high conductivity. Table 1 provides an overview of four wires we chose for closer examination. All of them exhibit high electrical and thermal conductivity and are well solderable.

Name	Material	Thickness	Resistance
Textile Wire 31604143	Cu/Ag20	0.06 mm	6.05 Ω/m
Textile Wire 30901494	Cu/Ag20	0.07 mm	4.44 Ω/m
Textile Wire 31605093	Cu/Ag20	0.15 mm	0.97 Ω/m
Verowire	Cu	0.20	0.86 Ω/m

Table 1. Enameled wires tested for their embroidery suitability. The thicker the wire, the smaller the resistance Ω/m.

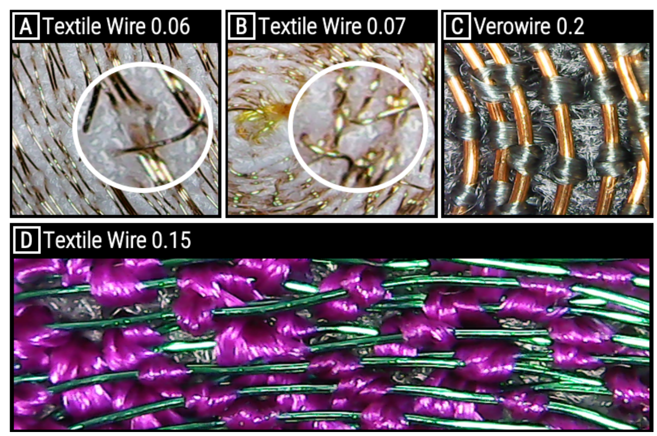

Figure 3. The thin versions of the Textile Wire tended to break (A,B), while a thicker wire does not allow tight stitches (C). We settled on the Textile Wire with a diameter of 0.15 mm as the most useful for our approach (D).

We conducted an informal experiment to find the thinnest wire from this set, still feasible for the fabrication of a dense Archimedean spiral with an outer diameter of $d = 50$ mm. The turn spacing was chosen 1.5 times bigger then the diameter of the wire, so that the needle does not break the wire of neighboring turns. All samples were embroidered with a Tajima SAI[1], in combination with digitizing software *Creator* from Pulse Microsystems Ltd. and a custom Python script for generating spiral traces from the given spiral parameters [2].

[1] MDP-S0801C: http://sai.tajima.com/en
[2] https://mitmedialab.github.io/spiral/

The results are shown in Figure 3. The thinnest wires (e.g. 0.06 mm, 0.07 mm) proved difficult to embroider as they are very prone to wire breakage during embroidery. Also reducing the embroidery speed from a maximum of 800 to 300 stitches/min to reduce stress on the wire, did not yield better results. The Verowire with a diameter of 0.2 mm could be embroidered without problems, yet limited the turn count at equal diameters. We settled on a 0.15 mm diameter wire which is composed of a copper core covered with concentric silver plating for corrosion resistance. The wire is insulated with a polyurethane enamel coating, which makes it washable up to 60°C, weakly dyeable and easily dryable[3].

Fabrication

An embroidery machine commonly utilizes a rotary hook to create lock-stitches, thereby fixing upper and lower thread onto the base fabric. Starting from the spool, upper thread passes through thread guides, take-up lever, and the needle before it is entwined with the bobbin thread on the textile. When using a wire as an upper thread instead of a conventional embroidery yarn, the wire is bent at many positions during the embroidery process while experiencing high tensile forces. This results in many wire breaks and prevents consistent embroidery. To avoid this, we use the wire as a bobbin thread, which is unspooled from within the bobbin case and does not have to pass steep angled turns before it is entwined with the upper thread. This significantly reduced the risk of wire breaks and allows for a consistent stitch quality.

As an upper thread, we used a 270 dtex polyester multi-filament yarn from Amann, which is optimized for embroidery. We prefer to use a thin upper thread to minimize the distance between coil turns.

After approximately 30 stitches, the process is paused to move residue wire, left by the embroidery machine during the initial stitch. This is required to prevent the beginning of the wire of being stitched over, and consequently not being accessible for connecting it to the circuit. This is challenging when starting embroidering at the coil's center, therefore we start stitching from the outside and progress towards the center.

By embroidering insulated wires we can fabricate coils with high turn density. E.g., with a thread of thickness of 0.15 mm, a coil with 300 turns would result in a diameter of 90 mm. However, we found that a minimum distance of the wires diameter must be kept between turns, as too closely placed stitches can result in wire breaks. The coil's turn spacing is limited by the diameter of the embroidered wire. To limit the stress applied to the wire and to avoid wire breakage, the turn spacing has to be chosen carefully. We empirically found a value of wire diameter times 1.5 as a viable minimum.

Furthermore, we conducted an evaluation regarding the effect and applicability of different fabric substrates, including twill weave (BadgeTex 2900 twill weave with 330 g/m^2), plain weave (SEFAR Acoustic, 280-12), and leather (Lecapell) - cf. Figure 4. In embroidery, denser base materials allow for more accurate stitches. Based on prior experience with embroidery, we primarily used the twill weave, as it allows for sub-millimeter precision in positioning of stitches and shows little tendency to frail when trimmed. It comes with the top cloth pressed onto a polyester fleece stabilizer, to prevent warping. This base material in combination with the embroidered coil forms the diaphragm of our speaker design. Diaphragms are generally optimized for operating at certain frequency ranges using a variety of different materials. Therefore, to ascertain the impact of the fabric substrate on the performance of our sonic transducers, we further manufactured coils using fine weave and leather as substrates.

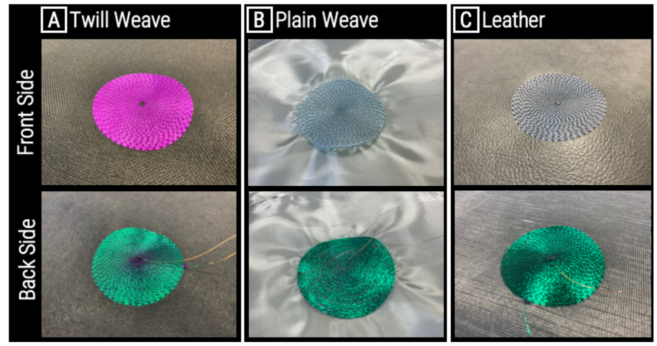

Figure 4. Three different fabric substrates and their influence to the embroidered coil shape have been evaluated.

coil diameter	turn count	turn spacing	wire length	electrical resistance	inductance	fabric substrate
25 mm	44	0.25 mm	1.93 m	2 Ω	40 µH	Twill Weave
50 mm	94	0.25 mm	7.82 m	8 Ω	125 µH	Twill Weave
100 mm	194	0.25 mm	31.37 m	32 Ω	1078 µH	Twill Weave
50 mm	47	0.50 mm	3.91 m	4 Ω	64 µH	Twill Weave
50 mm	94	0.25 mm	7.82 m	8 Ω	125 µH	Leather
50 mm	94	0.25 mm	7.82 m	8 Ω	125 µH	Plain Weave

Table 2. Parameters of the speaker coils which have been evaluated.

The performance of these fabric substrates in combination with different additional parameters have been evaluated, which we describe in the following sections, cf. Table 2. The diameters have been chosen to both correspond to the common sizes of treble speakers and so that the resistance is not lower than the usual speaker impedance ratings. Through that we ensure that the voice coil can be driven by an off-the-shelf audio amplifier. The turn count resulted from the turn spacing we defined.

EVALUATION

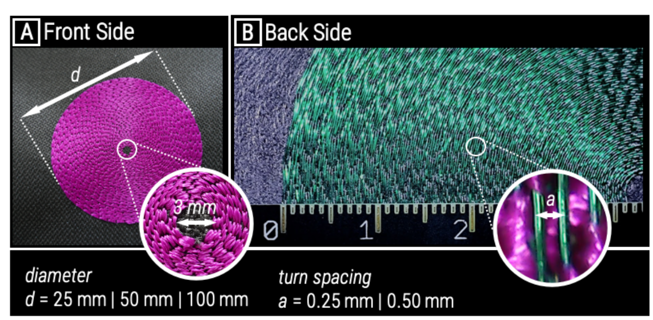

Figure 5. Different coil patterns have been embroidered varying the different parameters.

[3] http://www.textile-wire.ch/en

To evaluate the performance of our approach, we conducted experiments with six different embroidered speakers. For each speaker we used two identical coils on top of each other.

For each sample, we investigated impedance and frequency response. Additionally we examined the wire length and respectively the electrical resistance. We evaluated different coil sizes (25 mm, 50 mm, 100 mm), turn spacings (0.25 mm, 0.50 mm) and turn counts *t* (44, 94, 194), cf. Figure 5. The coils were embroidered onto different fabric substrates as discussed before.

Apparatus

The textile speaker under test was clamped to a 10×10 cm frame, allowing for an exact, repeatable, and plain positioning of the two sandwiched coils. The frame was then suspended between two aluminum beams using nylon yarns to minimize resonances of the fixture. To shield the recording of the stimulated textile speaker from unwanted reflections, we built a small box for sound insulation (80 × 80 × 80 cm) with sound-absorbing foam, see Figure 6.

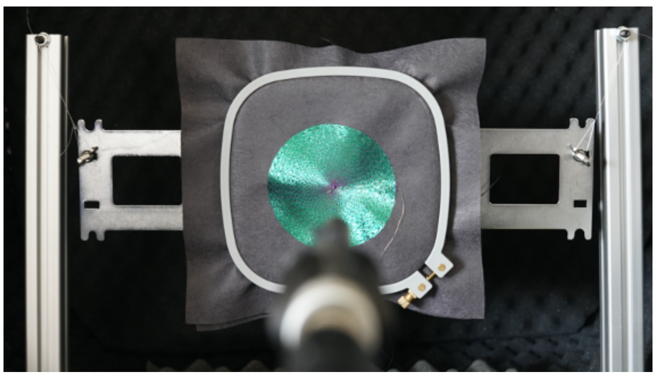

Figure 6. The opened sound-absorbing test chamber with a suspended 50 mm diameter textile speaker about to being tested.

Procedure

The test signals were generated by a Steinberg UR12 audio interface and amplified via the class-D audio amplifier TDA7498, driven by a 24 V power supply. The voice coil was directly fed with the amplified signal. The bias coil was driven with a rectified signal smoothed with a 1000 µF capacitor. Before recording the frequency response of the speaker being tested, the amplitude (dBFS) and respectively the voltage was adjusted in software, so that 0.5 Ampere were consumed by the amplification circuit when driving the speaker with a frequency of 1 kHz. This was done to achieve comparable powers consumed by the tested speakers. Driving all the speakers with the same voltage would result in considerable differences in amplitude, and would even destroy the coils with lower resistances.

The sound emitted by the speakers was measured using a *Behringer ECM8000* high precision condenser measurement microphone that was positioned at 30 cm distance to the embroidered speaker and connected to the *Steinberg UR22 MK2* audio interface. We stimulated the embroidered speakers using frequency sweeps from 200 Hz to 20 kHz. The duration of each measurement was 43.7 s including 8 sweeps, 256k samples each. For generating and recording the frequency responses we used the audio measurement software Room EQ Wizard (REW).

Results

Figure 7 (A) shows the frequency response of our embroidered coils (diameter sizes of 25 mm, 50 mm, and 100 mm).

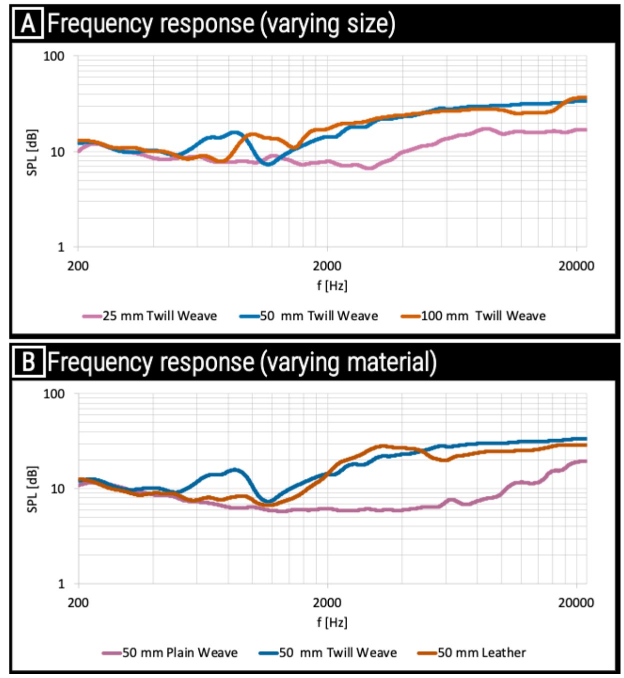

Figure 7. Frequency response of our coils using different sizes (A) as well as different fabric substrates (B).

As the chart clearly shows, all of them can reproduce high frequencies very well, the reproduction of frequencies below 2 kHz was comparable weak, especially with the smallest size of 25 mm. This chart also shows a significant increase of the SPL (dB) in the frequency range of 1,500 Hz - 20 kHz with a mean value of 29.34 dB ± 4.88 dB for the coil with a size of 50 mm, compared to a mean value of 14.63 dB ± 3.01 dB (25 mm) and to a mean value of of 27.71 dB ± 4.84 dB (100 mm).

Figure 7 (B) shows the frequency response of the embroidered coils with size of 50 mm, using different substrate materials. While the chart clearly shows a very weak reproduction for the plain weave material, we can reproduce again high frequencies well for the samples, embroidered on the twill weave, and on leather. Again, it also shows a significant increase of the SPL (dB) in the frequency range of 1,500 Hz - 20 kHz with a mean value of 21.19 dB ± 5.92 dB for the coil embroidered on the twill weave, compared to a mean value of 25.46 dB ± 3.49 dB for the coil embroidered on leather, which leads to the conclusion that it is good if the substrate textile is a little stiffer and less air permeable as it provides a better response.

Figure 8 shows the results for the impedance measurement varying different parameters. The evaluation is based on the

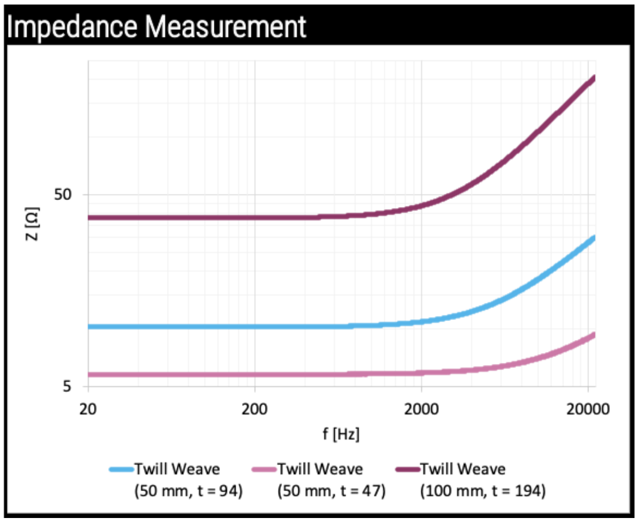

Figure 8. Impedance measurement.

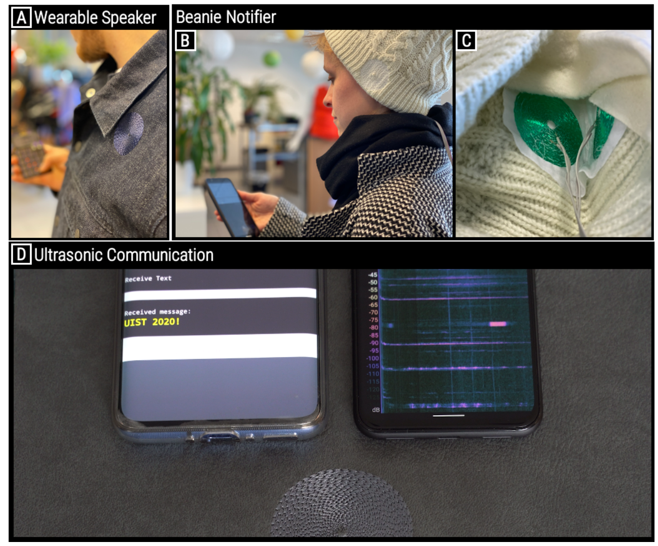

Figure 9. Three different demonstrator applications have been designed and implemented, including a wearable speaker for a handheld synthesizer (A), a beanie notifier (B, C), and an ultrasonic communicator (D).

measurement design as described in REW[4], with a sensing resistor of 1 kΩ. The calibration and measurement was done using the line output of the *Steinberg UR22 MK2* audio interface. The impedance measurement shows that the 100 mm coil has a high impedance rise at frequencies beyond 4 kHz. Concluding it is preferable to use smaller coils or lower turn count for high-frequency applications.

Summarizing, we would suggest using the Textile Wire with a diameter size of 0.15 mm and a resistance of 0.97 Ω/m in combination with a coil size of 50 mm or 100 mm, depending on the use case and a turn space of 0.25 mm on a substrate fabrics, which has low air permeability.

APPLICATIONS

In this section and the supplementary video, we present four example applications (see Figure 9) that show our embroidered coil in action. The demonstrated applications combine the advantages resulting from the speaker's flexibility and thin form factor in real-world scenarios.

Wearable speaker

In the first application (see Figure 9 (A)), we demonstrate a textile-based mobile speaker for a handheld synthesizer. We used the Pocket Operator PO-20, with a textile-speaker which we embroidered into the front pocket of a Jeans Jacket. The diameter size was 50 mm.

Beanie notifier

Figure 9 (B, C) shows a beanie with an integrated embroidered speaker. In comparison to existing approaches, the speaker is directly integrated into the textile while preserving the flexibility of the garment. The speaker is placed directly at the ear of the user and, just as headphones, can only be heard by the user if the amplitude is adjusted accordingly. It is well suited for unintrusive notifications.

Inaudible communication

Building on the wide frequency range capabilities of our speaker, we demonstrate its dynamic possibilities by using it as a transducer for audible and inaudible near-ultrasonic communications. We validated our system with two different modem protocols: quiet.js[5] and chirp.io[6] which can communicate with a frequency around 19 kHz. Figure 9 (D) illustrates the successful communication by visualizing the spectrogram[7] of the audio signal and the resulting message "UIST 2020" transmitted.

DISCUSSION AND LIMITATIONS

In this paper, we have focused on the design, implementation and characterization of a flexible textile speaker as an output device for smart textile applications. Additionally, our implementation of the embroidered coils allows for additional properties and functionalities, which will be shortly discussed. Although they are out of the scope of this paper, we judge them viable areas that may be addressed in future work.

Stretchability

For investigating the stretchability of our speaker, we additionally embroidered a speaker onto a jersey fabric as seen in Figure 10. The embroidered speaker itself wasn't designed to be stretched. Nevertheless, we achieved fairly good results and the embroidered coil was robust enough not to break when stretching it as much as possible by hand. In the scope of this paper we did not evaluate the speakers performance while being stretched. A circular zig-zag stitch could enable greater deformation of the coil. Sendrolini et al. [46] and Patino et al. [13] show, for instance, embroidered planar zig-zag inductors, that are stretchable and therefore optimal for elastic

[4] https://www.roomeqwizard.com/help/help_en-GB/html/impedancemeasurement.html

[5] https://github.com/quiet

[6] https://github.com/chirp

[7] https://borismus.github.io/spectrogram/

fabrics. Their results of the magnetic interference test did not fail – even when the textile has been stretched up to 132%. We, therefore, think that we could also achieve similar results by applying a zig-zag shape to our coil design.

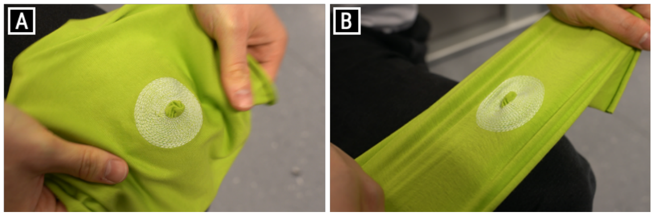

Figure 10. An embroidered coil design on a stretchable jersey fabric (A) was possible and even once fully stretched, it did not destroy the speaker (B).

Safety issues and tactile feedback

In contrast to electrostatic speakers [19, 20, 21, 22, 45], dynamic speakers as in our approach do not require high-voltages and are therefore more safe to touch. Similarly to the vibrotactile widgets (cf. printed actuators and sensor), i.e. [12, 43], the speakers can provide mild tactile feedback. When touched by the user, they still function as a speaker.

Microphone

The easiest way of transforming our speaker approach using two flat embroidered coils into a microphone would be the implementation of a dynamic microphone – without using a permanent magnet. We simply apply a direct current to one of the coils to generate a constant magnetic field. When the other coil is vibrating through excitation by an acoustic wave, voltage is induced in the moving conductor. The voltage can then be amplified and converted to a digital signal for further processing or recording.

Audible sound

Our design and implementation is not focusing on high-fidelity sound reproduction. Instead, the embroidered speaker is designed to produce audible sounds for notifications or to replay sounds in scenarios where audio quality is not key but low weight and high flexibility are a more important factor. Additionally, we aimed for inaudible applications such as near-ultrasonic communication.

Another option to get a better sound quality would be to use a meshed membrane as proposed by Bradley et al. [2].

Power consumption

To improve power consumption, our circuit could be enhanced by the usage of an envelope follower. It would allow detecting a minimum threshold in the signal amplitude to dynamically switch the power of the bias coil.

Magnetic field strength

As illustrated in Figure 11 (C), we compared the magnetic field generated by the magnet (D) from a wireless headphone[8] with the field generated by our embroidered coil powered by a 9V battery (at 346 mA), the field generated by our embroidered coil which is about 6 times lower (1159 µT vs. 7024 µT).

To further increase the volume of the speaker, two or more embroidered coils can be layered and connected in series to achieve a higher turn count and thereby a stronger magnetic field. The resulting coil should be used as the bias coil because of its resulting higher impedance. A lower impedance is expected to have a better power efficiency at high frequency AC, thereby a lower turn count for the voice coil is preferred. Additionally, a ferromagnetic thread with high magnetic permeability can be embroidered in the middle of the coils as a ferrite core to focus the magnetic field at the center.

One of the goals in our design was the avoidance of rigid permanent magnets, as they are not flexible, heavy, and difficult to fix to the textile. In contrast to our method, magnetoresponsive polymer-coated copper substrates could be used as permanent magnet, to avoid the mentioned downsides. These materials are coated with magnetoresponsive PNIPAM-based microgels and provide excellent magnetic properties [8, 57, 32]. We see potential in using these microgels in combination with copper-based threads, which again could be embroidered accordingly.

Heat development

We examined the heat development and dissipation of different coils being powered by 6 V, 12 V, and 24 V depending on their overall resistance. With increased temperature, the resistance increased up to 25% at 100°C compared to the resistance at 24°C.

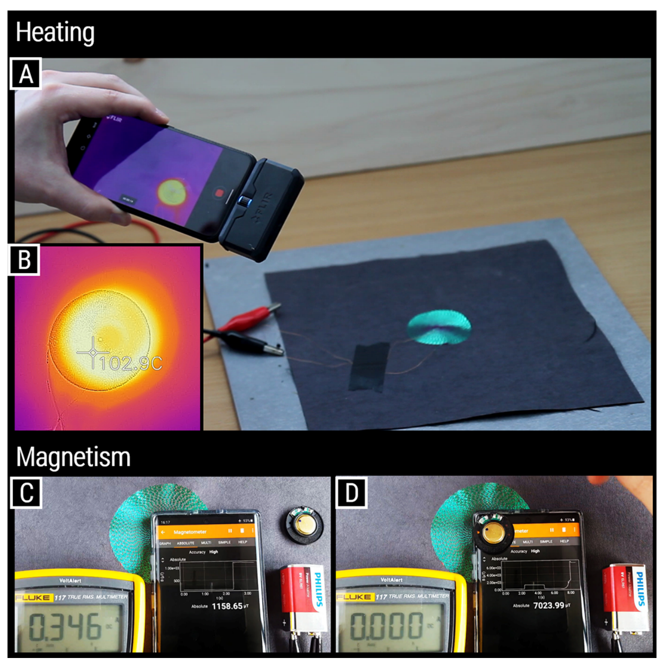

Figure 11. Limitations of our approach. Measurements with a thermal imaging camera show that the coil heats up significantly if it is powered with a high constant current (A-B). We also compared the magnetic field generated by the coil (C) to a magnet of a headphone speaker (D).

[8] http://Amzn.com/B07XKGCKXM (or http://archive.is/7ZLPM)

To avoid overheating, the current passing through the biasing coil should be limited, while only being powered when an audio signal is emitted. For short signals, as needed for audible notification sounds or inaudible communication signals, the current limit for the bias coil can be set higher (up to 1 A) as it is powered only for a very short time.

Litz wire

Depending on the application, it might also be worth thinking about using different wires, as the used Textile Wire has a fairly high resistance compared to that of more common voice coil wires. Especially for use cases, where high frequencies are more important, *litz* wires are a good alternative. These wires – as they form a bundle of individually insulated conductors – are designed to reduce the skin effects and are therefore optimal at high frequencies from kilohertz to the megahertz range. The litz wire must be chosen depending on the frequency range, as the number of threads and their thickness change their resistance and inductance. Various online resources exist to help for this choice and the manufacturer YDK provides a useful chart[9] for example.

CONCLUSION AND FUTURE WORK

In this paper, we demonstrated the design and implementation of an embroidered speaker without using a permanent magnet. Our proof-of-concept prototype consists of two flat spiral coils, stacked on top of each other. The two coils are fabricated by embroidering an isolated, thin (0.15 mm) and highly conductive wire. We carefully evaluated different designs and performed several experiments, varying different properties of the coil, including size, turn counts, turn spacing, and different substrate fabrics. The experiment results revealed that we can produce audible sound with a broad frequency range (1,500 Hz - 20 kHz) with with a mean value of 29.34 dB $\pm$ 4.88 dB SPL for the coil with a diameter of 50 mm.

For future work, we plan to investigate in more detail alternative yarns, including the litz wires as discussed in the section before. Especially, for the non-audible use cases these wires seem to be an excellent alternative to our used Textile Wires. For focusing the magnetic field to increase the effective volume we want to experiment with ferromagnetic thread as an iron-core for the coils. Another promising idea is the use of spacer fabrics between the coils to reduce distortion resulting from collisions of the coils.

Additionally, we also want to integrate the coils into the textile during the fabrication of the textile itself. The prototypes by Fobelets et al. are highly motivating and show the possibilities of developing a knitted version of a speaker [10, 9].

Finally, we also see great potential in combining multiple coils into one array to achieve a more powerful speaker, cf. Rowland's flexible audio speaker array [44]. Alternatively, we also would like to explore shapes that are beyond a simple circle, as proposed by Chong Loo et al. [30].

[9] http://hfLitzWire.com/litz-wire-product-list-in-stock

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