FLECTILE: 3D-Printable Soft Actuators for Wearable Computing

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ABSTRACT

Rapid prototyping and fast manufacturing processes are critical drivers for implementing wearable devices. This paper shows an exemplary method for building flexible, fully elastomeric, vibrotactile electromagnetic actuators based on the Lorentz force law. This paper also introduces the design parameters required for well-functioning actuators and studies the properties of such actuators. The crucial element of actuator is a helical planer coil manufactured from "capillary" silver TPU (Thermoplastic polyurethane), an ultra-stretchable conductor. This paper leverages the novel material to manufacture soft vibration actuators in fewer and simpler steps than previous approaches. Best practice and procedure for building a wearable actuator are reported. We show that dimension of actuators are easily configurable and can be printed in batch-size-one using 3D printing. Actuators can be attached directly to the skin as all the components of FLECTILE are made from biocompatible polymers. Tests on the driving properties have confirmed that the actuator could reach a broad scope of frequency up to 200 Hz with a small voltage (5 V) required. A user study showed that vibrations of the actuator are well perceivable by six study participants under an observing, hovering, and resting condition.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **Interface design prototyping**; • **Hardware** → **Sensors and actuators**.

KEYWORDS

wearable, conductive polymer, tactile soft actuator, 3D-printable

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1 INTRODUCTION AND RELATED WORK

Previous researches have greatly explored tactile interfaces for human computing (e.g. [1, 11]). Various driving strategies have emerged such as pneumatic [10], optical [13] and electromagnetic [7]. Lots of efforts focused on electromagnetic actuation because of simplicity to control and realize desired functions. To build soft electromagnetic actuators, often liquid metal alloy (LMA) was applied [2, 5, 6]. However, both spraying technology and injection methodology utilized during the fabrication in related research [2, 5, 6] requires a series of complex process steps, higher cost and, in general, much efforts. Yu et al. [12] presented a holistic, flexible on-skin electromagnetic actuator concept, where a fixed coil moves a magnet up and down freely. However, the materials for coils are common copper traces encapsulated in polyamide, requiring substantial manufacturing overhead. Table 1 presents a detailed comparison among related researches mentioned above. Differences from material, fabrication, flexibility and application perspectives are considered. The table illustrates how much easier the manufacturing process of our method, FLECTILE, is compared to related work. We also compared how related research achieves actuation by looking into the different principles within similar applications of tactile interfaces and FLECTILE as depicted in Table 2.

Latest advancements from material science proposed conductive, highly flexible materials based on TPU or PDMS *capillary* induced with silver particles [9], to, e.g., build flexible interactive human on-skin interfaces [8]. In our work, we hypothesize that capillary Ag-TPU applies for building 3D-printable, human-wearable actuators. To our knowledge, we present the first skin-applicable, 3D-printable soft actuator. Therefore, we make the following contributions:

- comparison of soft actuators from related work
- manufacturing process for fully 3D-printable soft actuators
- evaluation of the human perceivability of the approach

2 FLECTILE: FLEXIBLE TACTILE ACTUATOR

We present flexible tactile actuators (FLECTILE) that are manufactured in just two entirely 3D-printing-based steps with little manual efforts required.

Table 1: Comparison of different electromagnetic actuators based on material, fabrication process, application and flexibility.

Name	Fabrication Method and Process		Flexibility	Application
EGaIn Alloy [2]	Injection	(1). laminate the silicone (2). cover a micro carbon hollow (3). cure the micro carbon hollow (4). inject the LMA into hollow filament (5). insert the electrodes (6). form it into the helical shape	stretchability depend on the tube and substrate	Robotics & Vibrotactile Feedback Display
Ga-In Alloy [5]	Injection	(1). wash silicone tubes (2). inject the LMA into tubes (3). build electronic connection (4). seal the metal pins (5). wound tubes into helical shape (6). cast the silicon (7). cure the actuator (8). repeat the process *(6)* and *(7)* (9). trim to desired shape	stretchability depends on the tube and substrate	Robotics
Ga-In Alloy [6]	Spraying	(1). coat a PDMs layer (2). cure the substrate (3). cover the film with a mask (4). print the LM traces (5). remove the mask (6). spin to coat a PDMs layer (7). cure the actuator	stretchability depends on the PDMs substrate	Robotics
Copper Wire [12]	Moulding	(1). place a Cu coil (2). sub-merge the Cu coil (3). bake for the first time (4). seal the coil again (5). cure the actuator (6). trim to desired shape	stretchability depends on the silicone substrate	Haptic Interface
Ag-TPU FLECTILE	**Fully 3D Print**	**(1). print a TPU substrate** **(2). print traces** **(3). cure the actuator**	**both coil and substrate are fully elastomer based**	**Haptic Interface**

Table 2: Actuators in related work follow different driving modes to induce vibrations.

Name	Moving Parts
EGaIn Alloy - [2]	permanent magnet moves upward and downward
Copper Wire - [12]	permanent magnet moves upward and downward
Ag-TPU - FLECTILE	**the coil moves upward and downward to generate vibration directly on people's skin**

2.1 Working Principle and Design

FLECTILE operates based on the Lorentz force principle. A conductor generates a magnetic field around it once current flows. The combination of a state switching electromagnetic coil and a permanent magnet drives the actuator.

We present a novel design where, instead of single-sided coils in related works, the conductive loops are on both sides of the substrate. This principle allows current flowing in a clockwise and counterclockwise direction, respectively. According to Ampere's Law, the clockwise and counterclockwise loops with current flowing generate a magnetic field in the same direction. Therefore, the actuator field strength of the Ag-TPU traces enhances to match closer with single-coil actuators based on liquid metal alloy. Figure 1 shows the working principle of FLECTILEs. We choose to place FLECTILE on the forearm, which fits potential future applications.

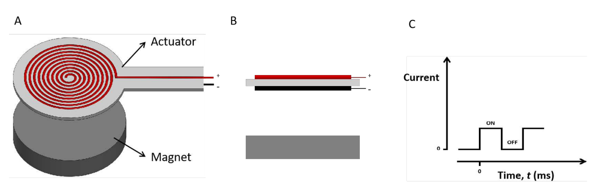

Figure 1: (A). 3D view of the FLECTILE with printed coils designed in clockwise and counterclockwise on two sides of the substrate; (B). Front view of the FLECTILE ; (C). Driving method: 5V DC power switching on and off.

2.2 Manufacturing Process

The soft actuator consists of two parts: a fully 3D-printed electromagnetic actuator and a permanent magnet. Printing an actuator requires two simple, mostly automated steps. Figure 2 shows the fabrication of the electromagnetic actuator. First, a Thermoplastic

Polyurethane (TPU) substrate (0.8 mm thick) with an all-through hole (1mm diameter) in the center was printed with semi-flexible filament TPU 95A (Ultimaker) using a Fused Filament Fabrication (FFF) type 3D printer (Ultimaker). Next, a Direct Ink Writing (DIW) type 3D printer (Voxel8 Developer's Kit printer) equipped with 400 µm nozzle prints *capillary* silver TPU ink (Ag-TPU) traces, with 21 vol% Ag on both sides of the TPU substrate. The printed coils' design allows current flowing clockwise and counterclockwise. A droplet of the capillary ink was filled into the substrate center hole to interconnect the two coils. The capillary Ag-TPU ink follows the process presented in previous research ([9]). The electrical conductivity was determined to be 2884 ± 165 S/cm using a four-point probe method. Finally, two copper wires that connect to the power supply were glued on the actuator using the same ink. The actuator dries at room temperature for eight hours.

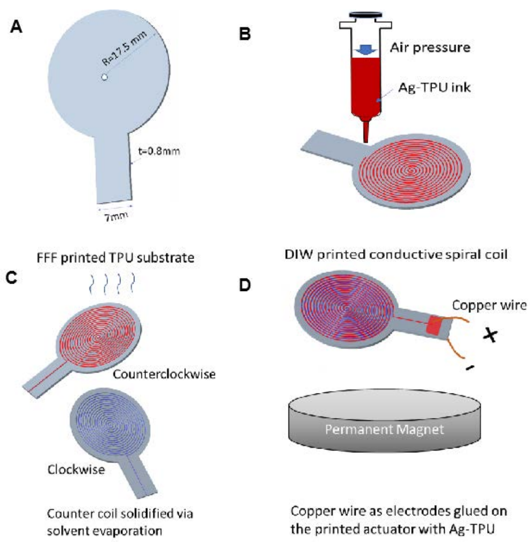

Figure 2: (A). print a TPU substrate with a 1mm all-through hole in the center; (B). print capillary Ag-TPU ink traces on both sides of the substrate; (C). cure the trace; (D). connect copper wires and trace using the same Ag-TPU ink.

Moreover, FLECTILE actuators can be printed freely in varying sizes. According to wearability constraints by Zeagler [14], weight and size limits of the area on the forearm are 226g and much less than 40mm. Figure 3 shows different actuators in dimension, which is far below the limitations (including, e.g., a 100 g magnet).

3 EVALUATION

To understand the applicability of FLECTILEs, we explored general actuator properties and conducted a user study. The actuator with 400 µm trace width, 35 mm diameter, and 0.8 mm thickness was applied. The diameter size was chosen based on related work on soft actuators by Guo et al. [6]. The size of the magnet was Ø42x9 mm with 55 kg holding force. The distance between the permanent magnet and the actuator was 1 mm. The technical basis is an *Arduino Duemilanove* microcontroller with a 5 V operating voltage.

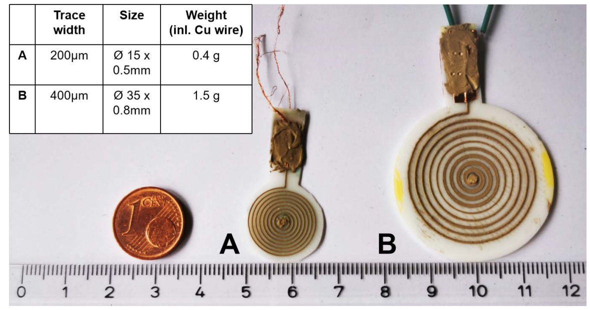

Figure 3: Different diameters and trace width/distance

3.1 Actuator Properties

To characterize the actuator under different conditions, we set up three experiments to test the most stable working frequency, the maximum working distance and the effect of different magnetic field respectively. In the first experiment, we placed a camera facing the actuator from the side and record the performance defined by stable, continuous actuation. We characterized the working performance according to electric actuation frequency by iterating over the range of 1-80 Hz. This scale is a consensus on the limits of human exposure to vibration [3, 4]. From 1 to 10 Hz, we chose step-size of 2 Hz, and from 10 to 80 Hz step-size of 10 Hz. The video link is enclosed in the attachment. We also characterized the upper frequency limit by iterating at step-size ten. Visible vibration could not be observed above 200 Hz. Figure 4 illustrates how the normalized amplitude changes in regards to actuation frequency extracted frame-by-frame from a video. The frequency that the actuator works robustly ranges from 1 Hz to 30 Hz, but an unexpected, continuous small pulse emerges above 40 Hz. We hypothesize that the magnetic field is not strong enough and before the actuator changes direction it is again pulled in the opposite direction. The actuator has the most stable performance at around 20 Hz to 30 Hz. Thus, we applied 20 Hz in the user study. FLECTILE is compatible with a broad scope of frequencies for different applications.

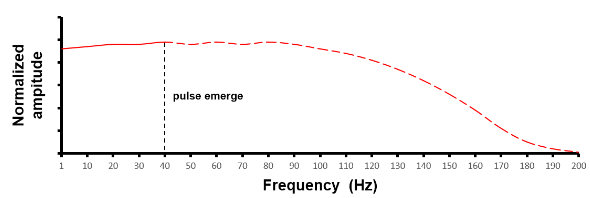

Figure 4: Exp. 1, Actuator response frequency: 1-200Hz

In the second experiment, we defined the maximum working distance. We 3D-printed cubes from 10-20 mm height (working distance ranges from 1 to 11 mm) at a step-size of one millimeter. Visible vibration could not be observed when the working distance between the permanent magnet and the actuator exceeded 7 mm (Table 3). Figure 5 shows the 3D-printed cube.

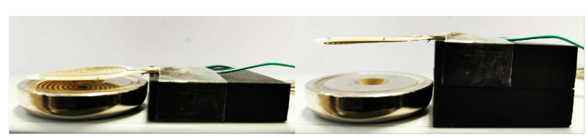

Figure 5: Exp. 2, 3D-printed cubes for varying distance

In the third experiment, we investigated how different strengths of magnetic field might influence the performance of FLECTILEs. We applied four different Neodymium disk magnets. The results in Table 3 indicate that a weaker magnetic field could also trigger the actuator compared to the strong magnet (55kg holding force) used in our initial experiments. Thus, by relying on small sized magnets with weaker magnetic field, FLECTILEs can be optimized to be more compatible with the human body.

Table 3: Results of Experiment 2 and 3

Design Parameter	Set Up	Result
Distance	Fix FLECTILE on the cubes with different height	Actuation visible from 1-7 mm distance
Magnetic field	Magnet sizes and corresponding holding forces: Ø15x3 mm (4.5 kg) Ø15x5 mm(8 kg) Ø20x3 mm(12 kg) Ø30x5 mm(18 kg)	Actuation visible with Ø30x5 mm and Ø20x3 mm

3.2 User Study

To study how good vibrations at 20 Hz caused by the actuator can be perceived, we recruited six participants through a sample of convenience (age range: 19 to 40; mean age: 27.8, 4 males, 2 females). According to the two-point discrimination sensitivity test on body locations, the finger is the most sensitive area[14]; thus, we asked participants to test FLECTILE with their fingers. Participants were recruited from our lab and not rewarded for their participation.

We tested the actuator in four scenarios and in each scenarios participants were asked to report their feedback three times. First, we asked participants to *observe* the actuator moving. Second, we asked them to *hover* their fingers over the actuator without touching it before it actuates. Then, we used a 3D-printed case that integrates the actuator and magnet so it can apply on the user's finger. We asked participants to first *rest* their finger in a steady position and then also to lightly *press* the actuator. Figure 6 illustrates the principles of the scenarios and the 3D printed case.

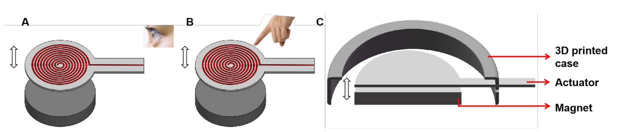

Figure 6: (A). ***Observe*****; (B).** ***Hover*****; (C). Section view of 3D printed case.**

All participants expressed they could *observe* a noticeable vibration, and also that they could feel the vibration quickly and clearly under the *hover* and *rest* conditions. However, three of the six participants felt nothing when they *press*ed the actuator, but the effect depends on the applied force. Additionally, all participants felt comfortable and did not perceive the actuator as intrusive.

4 DIY: HOW TO BUILD A FLEX ACTUATOR

In this section, we demonstrated a "cookbook style" instruction on how to build FLECTILEs simply and effectively.

Ingredients.

- Ultimaker 3 TPU 95A filament (2.85 mm, 750 g, white);
- Capillary silver TPU ink (Ag-TPU, including 21 vol% Ag);

Apparatuses.

- Fused Filament Fabrication (FFF) 3D printer;
- Direct InkWriting (DIW) type 3D printer;
- a needle (1 mm in diameter);

Instructions.

- design the mold for substrate with CAD software (parameter of the sample actuator is shown in Figure 2. (A));
- print substrate using TPU 95A filament from FFF 3D printer;
- print trace on one first using Ag-TPU ink and DIW printer;
- after 30 mins cure, print the trace on the other substrate side;
- let actuator sit at room temperature for 8 hours until cured;

5 WEARABLE APPLICATIONS

To show the applicability of FLECTILEs in a wearable context, we built two prototypes of applications as shown in Figure 7.

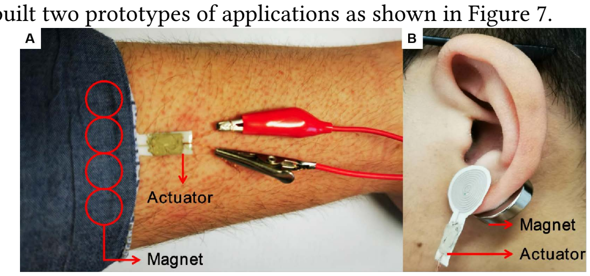

Figure 7: Application:(A). Vibration sleeves; (B). Earring-shaped haptic feedback system.

In Figure 7 (A), four magnets (red circles) are integrated in a textile sleeve, and the FLECTILE is placed directly on the forearm.

Another application where the actuator is placed on the earlobe illustrated in Figure 7 (B). We fixed the magnet with a double-sided tape on the back side of the user's ear and the FLECTILE should stay in place by bending the flexible wire around the ear lobe.

6 DISCUSSION AND CONCLUSION

This paper shows how to fabricate a wearable, skin attachable electromagnetic actuator. The main innovation of our actuator is the design of the 3D-printable soft electromagnetic inductor with 3D-planer helical coils made from soft, stretchable materials. The main advantage of FLECTILEs is that they can be manufactured in batch-size one rapidly using standard DIY equipment. The actuator is fully elastomer based, cheap because only little silver is involved, and ultra-light (0.4 g-1.5 g dep. on size). High durability and repeatability of the material has been shown in related work by Sun et al. [9].

We have evaluated FLECTILE from a material's and user's perspective. Our results suggest that FLECTILE has a wide working range of frequency and can generate and convey vibrotactile sensation. All participants were able to observe and feel the vibrations of the actuator. Three out of six participants reported that they couldn't feel the vibrations when pressing; however, with too much force used, not enough space is left for the actuator to vibrate.

The magnetic field generated by the traces depends on a set of factors, including the density of the coil, the applied current, and the conductivity of the trace material controlled by the fraction of silver. Different factors can be modified to create FLECTILEs in varying shapes and sizes and allow the principle to fit various and promising applications.

REFERENCES

[1] Ravinder S Dahiya, Leandro Lorenzelli, Giorgio Metta, and Maurizio Valle. 2010. POSFET devices based tactile sensing arrays. In *Proceedings of 2010 IEEE International Symposium on Circuits and Systems*. IEEE, 893–896.

[2] Thanh Nho Do, Hung Phan, Thuc-Quyen Nguyen, and Yon Visell. 2018. Miniature soft electromagnetic actuators for robotic applications. *Advanced Functional Materials* 28, 18 (2018), 1800244.

[3] International Organization for Standardization. 1978. *Guide for the evaluation of human exposure to whole-body vibration*. The Organization.

[4] JC Guignard. 1971. Human sensitivity to vibration. *Journal of sound and vibration* 15, 1 (1971), 11–16.

[5] Jianglong Guo and Jonathan Rossiter. 2020. Stretchable bifilar coils for soft adhesion and sensing. *Materials & Design* 190 (2020), 108545.

[6] Rui Guo, Lei Sheng, HengYi Gong, and Jing Liu. 2018. Liquid metal spiral coil enabled soft electromagnetic actuator. *Science China Technological Sciences* 61, 4 (2018), 516–521.

[7] J. Hey, T. J. Teo, V. P. Bui, G. Yang, and R. Martinez-Botas. 2014. Electromagnetic Actuator Design Analysis Using a Two-Stage Optimization Method With Coarse–Fine Model Output Space Mapping. *IEEE Transactions on Industrial Electronics* 61, 10 (2014), 5453–5464.

[8] Tobias Röddiger, Michael Beigl, Daniel Wolffram, Matthias Budde, and Hongye Sun. 2020. PDMSkin: On-Skin Gestures with Printable Ultra-Stretchable Soft Electronic Second Skin. (2020).

[9] Hongye Sun, Zongyou Han, and Norbert Willenbacher. 2019. Ultrastretchable Conductive Elastomers with a Low Percolation Threshold for Printed Soft Electronics. *ACS Applied Materials & Interfaces* 11, 41 (2019), 38092–38102.

[10] Y. Sun, Y. S. Song, and J. Paik. 2013. Characterization of silicone rubber based soft pneumatic actuators. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 4446–4453.

[11] Nicholas Wettels, Veronica J Santos, Roland S Johansson, and Gerald E Loeb. 2008. Biomimetic tactile sensor array. *Advanced Robotics* 22, 8 (2008), 829–849.

[12] Xinge Yu, Zhaoqian Xie, Yang Yu, Jungyup Lee, Abraham Vazquez-Guardado, Haiwen Luan, Jasper Ruban, Xin Ning, Aadeel Akhtar, Dengfeng Li, et al. 2019. Skin-integrated wireless haptic interfaces for virtual and augmented reality. *Nature* 575, 7783 (2019), 473–479.

[13] Hanafiah Yussof, Jumpei Takata, and Masahiro Ohka. 2008. Measurement principles of optical three-axis tactile sensor and its application to robotic fingers system. In *Sensors, Focus on Tactile, Force and Stress Sensors*. I-Tech Publishers, 123–142.

[14] Clint Zeagler. 2017. Where to wear it: functional, technical, and social considerations in on-body location for wearable technology 20 years of designing for wearability. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. 150–157.