A low voltage-powered soft electromechanical stimulation patch for haptics feedback in human-machine interfaces

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\textbf{ABSTRACT}

One grand challenge in haptic human-machine interface devices is to electromechanically stimulate sensations on the human skin wirelessly by thin and soft patches under a low driving voltage. Here, we propose a soft haptics-feedback system using highly charged, polymeric electret films with an annulus-shape bump structure to induce mechanical sensations on the fingertip of volunteers under an applied voltage range of 5–20 V. As an application demonstration, a 3 × 3 actuators array is used for transmitting patterned haptic information, such as letters of ‘T’, ‘H’, ‘U’ letters and numbers of ‘0’, ‘1’, ‘2’. Moreover, together with flexible lithium batteries and a flexible circuit board, an untethered stimulation patch is constructed for operations of 1 h. The analytical model, design principle, and performance characterizations can be applicable for the integration of other wearable electronics toward practical applications in the fields of AR (augmented reality), VR (virtual reality) and robotics.

\section{Introduction}

Wearable electronics having a variety of functions are desirable in seamless human-machine interface applications for the modern era (Rogers, 2017). These may include flexible sensors to detect environmental signals and wearable actuators to generate mechanical sensations (Zhong et al., 2019; Hu et al., 2021; Li et al., 2021b; Chu et al., 2018). Today, numerous wearable sensors have been developed to monitor physiological parameters relevant to human health conditions, such as electro-cardio signals, pulse waves, blood pressure, and body motions (Guo et al., 2018; Pu et al., 2017; Li et al., 2020; Zhu et al., 2020). On the other hand, the progress of thin and wearable soft actuators attachable to human skins powered by low voltages remains very challenging (Zhong et al., 2019; Hu et al., 2021; Zhu et al., 2020). For example, traditional actuator systems have utilized bulky and non-wearable linear resonators, eccentric rotating masses, and voice coils to generate mechanical stimulations (Pacchierotti et al., 2017; Zhang et al., 2002). Thin and soft actuators based on piezoelectric polymers such as polyvinylidene fluoride (PVDF) and its co-polymers have the advantages in making flexible, thin, and light-weight patches (Hu et al., 2021; C. Li et al., 2016). However, the high driving voltage requirements (in the range of hundreds of volts) are not desirable. In addition, actuators based on dielectric elastomer polymers has been demonstrated with haptics feedback applications but they require even higher driving voltages (in thousands of volts) in order to produce strong electromechanical responses by the thin polymer films (Rich et al., 2018; Christianson et al., 2018; Yin et al., 2020). In recent years, electret-based polymeric transducers have exhibited high electromechanical conversion efficiencies for applications in energy harvesters and sensors, which could be applicable in building thin and wearable actuators for haptic...
human-machine interfaces (Li et al., 2021a; Zhou et al., 2020; Tat et al., 2020; Zhong et al., 2016).

In general, human skins have four types of tactile receptors for haptic sensations as shown in Fig. S1a: (1) the tactile corpuscle (Meissner’s corpuscle, MC) sensitive to the light touch and texture changes of small areas under low frequency actuations; (2) the lamellar corpuscle (Pacinian corpuscle, PC) sensitive to energy stimulations of large skin areas under slightly higher frequencies; (3) the bulbous corpuscle (Ruffini ending, SA-I) sensitive to mechanical tensions deep in the skin; and (4) the Merkel nerve ending corpuscle (Merkel disc, SA-II) sensitive to sustained pressures (Gescheider et al., 2008; Chortos et al., 2016). The required stimulations of high pressure and deep into the skin to induce human sensations are difficult to generate by thin and soft polymer films. As such, this work focuses on low-magnitude stimulations on the MC and PC receptors based on flexible polymer films using a low driving voltage below 400 Hz.

A thin and wearable haptic electromechanical patch is proposed based on the “air-bubble” electret structure to accumulate and store electrostatic charges, with the annulus-shape contact design to induce high mechanical sensations. Together with a flexible lithium polymer battery as the power source and a bendable control circuit board, the system can produce haptic sensations wirelessly under a low driving voltage for human-machine interface applications up to 1 h in the prototype, as illustrated in Fig. 1a. The “air-bubble” electret structure helps...
accumulating and storing electrostatic charges to result in a high internal surface potential, which reduces the driving voltage requirement. The annulus-shape contact design helps stimulating both the MC and PC tactile receptors in human skins, which further reduces the threshold driving voltage. As a result, several advancements have been achieved when compared with the state-of-art works in polymer-based wearable actuators: (i) detectable haptic sensations on fingertips of volunteers under an ultra-low driving voltage range of only 5–20 V at 300 Hz; (ii) continuous and stable haptic stimulations with output variations of less than 5% after 78 million actuation cycles; (iii) a 3 × 3 actuators array for transmitting patterned haptic information, such as letters of ‘T’, ‘H’, ‘U’ and numbers of ‘0’, ‘1’, ‘2’; and (iv) an un tethered system powered by flexible batteries (7.4 V) and a circuit board for navigating direction demonstration.

2. Experimental section

2.1. Fabrication of haptic actuator

Three haptic actuators with sizes of \(2 \times 2 \text{ cm}^2\), \(3 \times 3 \text{ cm}^2\), and \(4 \times 4 \text{ cm}^2\) were fabricated in this paper. Each of the low voltage soft haptic actuator was formed by assembling three components (A, B, C), of which boundaries were fixed with double-sided tape (3M, 61 μm in thickness).

1) To prepare component A, Al tape (Detai Inc. with glue on the surface and the thickness of 100 μm) was adhered to an FEP film (DuPont Teflon®, thickness of 12.5 μm). Then, the FEP/Al film was pressed into wavy pattern (about 1 mm in length and over 0.2–0.5 mm in height) by the embossing process by pressed into the wavy pattern with two 3D printing mold inserts. Similarly, a PI tape (Bertech Inc. with the thickness of 165 μm) was pressed into annulus-bump shape. Then, the PI tape was adhered to the Al electrode of FEP/Al film as a supporting and isolating structure. Besides, another FEP film was adhered to the FEP film side of FEP/Al film to form air bubbles in between. Lastly, the FEP/ Air/ FEP/Al/PI structure was corona charged. 2) Component B had the same structure with component A except that the PI tape was not pressed and was flat. 3) To prepare component C, two pieces of Al tapes are adhered to both sides of a paper substrate (Genuine Origami Craze Inc., 70 gsm). Then, the Al/Paper/Al structure was pressed into wavy-shape pattern (about 5–20 mm in length and about 1–2 mm in height) with the assistance of a 3D printed mask. 4) Component C was sandwiched between component A and B with PI films on the outermost sides.

2.2. Characterizations and measurements

The surface potential of the samples was characterized by a Trek model 347 electrostatic voltmeter. For driving voltages of more than 20 V, a PI E-463 HVPZT amplifier was utilized and an Agilent 33220A functional generator was used to adjust the frequency. For driving voltages of less than 20 V, an Agilent 33220A functional generator was directly utilized. The output displacement of the actuator was measured by a Laser Doppler Vibrometer (LDV, Polytech OFV5000). The power consumption of a soft actuator was measured by a Keithley 6514 voltage meter, a SR570 current amplifier and a NI USB-6341 DAQ. The output force of the actuators was measured by an ATI Nano 43 Force Sensor.

3. Results and discussion

3.1. Design strategy

The annulus-shape contact design aims to induce strong responses from both the MC and PC receptors as shown in Fig. 1 b and Fig. S1 b. The prototype bump structure has a height of 0.5–1 mm to generate the “double gradient stimulation effect” from both inner and outer surfaces by inducing a large deformation and displacement on the skin to excite the MC receptors (Verrillo, 1962). On the other hand, the annulus-shape structure can stimulate the skin indentation effect to transmit large energy to the PC receptors (Makous et al., 1996). Fig. 1 e illustrates different layers of the soft actuator patch based on the 12.5 μm-thick Fluorinated Ethylene Propylene (FEP) films as the electret materials. The “air-bubbles” design in between the two FEP layers can increase the storages of electrostatic charges for high electromechanical outputs. The detailed fabrication processing steps are shown in Fig. S2. The top PI layer is shaped into the designed surface profiles such as the annulus-shape contact structure by using a mold insert and a pressing process, as shown in Fig. S3 (Lin et al., 1998). When the soft actuator is pressed by the fingertip of a volunteer on the top PI structure, a simplified model including the preload is depicted in Fig. 1 d and the detail working mechanism is described in the supporting explanation 1. When a positive electrical voltage is applied at the middle spring electrode, the system contracts due to the electrostatic force. If the applied voltage reduces to zero, the actuator recovers back to its original shape with the assistance of the spring force (Yin et al., 2020). The trapped air bubbles in the FEP/Air/FEP electret film can capture extra electrostatic charges on their inner surfaces as shown in Fig. S4 to result in a high surface potential with increased electromechanical coupling efficiency and reduced charge leakages for improved long-term stability (W. Li et al., 2016). The large number of electrostatic charges can induce a high built-in electrical field \(E_{ci}\), while the externally applied AC driving voltage can induce the external electrical field \(E_{ext}\). The combination of the two electrical fields results in varying electromechanical deformations controlled by the externally applied voltage. The surface potential generated by the electrostatic charges captured on the electret film are equal to the effect of DC bias voltage, which can reduce the AC driving voltage. The wavy-shape Al/paper/Al spring structure functions as both the elastic mechanical spring and the common electrical electrode.

Volunteer experiments are conducted by placing a reference soft actuator and a testing actuator (the same size of \(2 \times 2 \text{ cm}^2\) side-by-side for the left and right hands of a volunteer using their middle fingertips, as indicated in Fig. S5 for a total of 20 volunteers. At the beginning of these tests, volunteers have been asked to adjust the pressure they may apply on the actuator individually to have the best haptic sensations. The measured average preload value for the 20 volunteers is around 0.8 ± 0.2 N when the applied peak-to-peak AC voltages are 10 and 20 V, as shown in Fig. S6. The high applied voltage of 20 V results in high sensation levels in all frequencies as expected and the best haptic sensation is recorded at 300 Hz, as the resonant frequency of the tested actuator is around 300 Hz, which also belong to the most sensitive frequency range of PC tactile receptors (Gescheider et al., 2008; Chortos et al., 2016). As such, the reference actuator is driven constantly under an alternating voltage of 20 V at 300 Hz to give a strong haptic sensation intensity. The testing actuator is then excited under a randomly chosen applied voltage (5, 10, or 20 V) and frequency (10, 50, 100, 120, 140, 170, 200, 250, 300, 350, 400, or 500 Hz) for three times of each test. The haptic sensation level is labelled as “Level 0” (no sensation), “Level 1” (weak sensation), “Level 2” (similar sensation), and “Level 3” (strong sensation) as compared with that of the reference actuator and the results are plotted in Fig. 1 e. As expected, a high driving voltage induces a high electromechanical deformation and results in a strong average sensation intensity. The threshold or lowest AC driving voltage is at 5 V at 300 Hz to induce the haptic feedback sensations. For other frequencies from 50 to 400 Hz, as shown in Fig. S7, the required driving voltages increase slightly but they are all below 25 V, which is a drastic improvement as compared with the state-of-art works to meet the voltage regulation of 50 V for human skin. On the other hand, the average sensation intensity in the low frequency range of 10–150 Hz increases for the actuators with the annulus-shape bump structure. This is attributed to the larger displacements by the annulus-shape bump structure as compared to those of actuators with the cylinder-shape bump or flat surface. This result is further validated by the “adapting stimulus” experiments in Fig. S8 (Hollins et al., 2001; Verrillo and Gescheider, 1977; Gescheider et al., 1979). The adapting stimulus tests
are conducted by stimulating the middle fingertip with an actuation intensity of 9 dB above the “basic line” condition for a period of 6 min at 30 Hz and 250 Hz, respectively, to allow receptors to familiarize the sensational feelings. Afterwards, the threshold voltages are characterized again. After the 30 Hz adaption stimulation, it is found the threshold sensation voltage clearly increases for stimulations with frequencies below 150 Hz, suggesting MC receptors are more responsive to low frequency stimulations. On the other hand, after the 250 Hz adaption stimulation, the threshold sensation voltage increases for all frequencies, implying that both PC and MC receptors have similar responses for high frequency stimulations.

Fig. 2. Effects of electret structure design. (a) Optical image of a prototype FEP/Air/FEP/Al electret film. (b) Enlarged image showing the film composed of a flat FEP film and a wavy-shape FEP/Al film. These two films are adhered together with air bubbles in between during the Corona charging process. (c) An optical image of the FEP/Air/FEP/Al film pressed by the fingertip of a volunteer to illustrate that both the wavy-shape structure and air bubbles are preserved. (d) Electrostatic charge distributions in the FEP/Air/FEP/Al film showing many charges stored on the inner surface of the air bubbles. (e) Surface potential vs. time for the FEP/Air/FEP/Al film before and after physical contacts with an Al film. (f) Experiment and simulation results for the output energy of prototype actuators (size of 2 × 2 cm²) with respect to the electret surface potential. (g) Relative output energy vs. time for soft actuators based on a 12.5 μm-thick and single-layer FEP film, a FEP/Air/FEP/Al film (one-layer air bubble structure), and a FEP/Air/FEP/Air/FEP/Al film (two-layer air bubble structure), respectively.

3.2. Electret structure and prototype

Fig. 2a shows the optical image of a fabricated FEP/Air/FEP/Al electret film, with the enlarged view showing the detailed structure in Fig. 2b. An Al-tape is first adhered to a FEP film, and the system is pressed under a wavy-shape mold insert to duplicate the wavy pattern of ~1 mm in width and ~0.2–0.5 mm in height. A second flat, 12.5 μm-thick FEP film is placed on top at the FEP side of the FEP/Al film to form air bubbles. During a ~20 kV Corona charging process for 20 min, the two FEP films are adhered strongly due to the electrostatic field while the FEP/Air/FEP/Al film is charged with a high surface potential. The
wavy-shape and high stiffness of the Al tape (Fig. S9) prevent the collapse of the air bubbles during the normal actuator operations in Fig. 2c to help the storage of electrostatic charges and maintain high and stable surface potentials (Fig. 2d). Even the preload force applied on the FEP/Air/FEP/Al film is up to 10 N, the air bubble structure maintains the bubble shape (Fig. S10). However, if the air bubble structure is fully flattened, some induced charges can be neutralized to degrade the performance. The surface charge potential of a prototype FEP/Air/FEP electret film in the laboratory environment has been measured for 7 days to show a typical decay and stabilization process in Fig. 2e from \(-1100\) V as the original value to \(-750\) V as the final value. If a conductive Al film is applied on the metal side of the prototype FEP/Air/FEP/Al film, the surface charges can reduce quickly to \(-550\) V, but it remains stable afterwards as the internal charges around the air bubbles are mostly retained. In this work, the Corona charging process is set to produce more negative charges on the FEP film since it has better capacity to capture and store negative charges (Rychkov et al., 2012; Xia et al., 2003).

The displacement and output energy characterizations use the setup shown in Fig. S11. A 4 mm thick PDMS film is used to emulate the tissues of the fingertip and a stiff glass piece is placed between the soft actuator and the PDMS. A preload force \(F_{\text{preload}}\) is adjusted via a spring and the vibration displacement \(Y_s\) of the glass piece is recorded by a Laser Doppler Vibrometer (LDV). The output energy \(\Delta W_{\text{peak}}\) is estimated as (Supporting explanation 2):

\[
\Delta W_{\text{peak}} = 2F_{\text{preload}} \cdot Y_s \cdot \max
\]

where \(Y_s \cdot \max\) is the maximum vibration displacement relative to the neutral position. Fig. 2f shows measured output energy versus the surface potential of the FEP/Air/FEP electret film under a driving voltage of
20 V at 300 Hz, and a preload of 0.7 N. The surface potential of the film can be adjusted by the corona charging process (Fig. S12). The measurement results show approximate linear relationship between the output energy and the surface potential. The output energy reaches a maximum value around 0.41 μJ when the surface potential is around 450 V for the prototype in Fig. 2f and Supporting explanations 1 and 3. The simulation results follow a linear relationship, while the measurement results show an approximate linear relationship, which may be caused by the variation of mechanical properties during the test and the measuring errors.

Three different prototype films (size of 2 × 2 cm²) have been tested: 1) a single-layer FEP electret film (thickness of 12.5 μm), 2) a FEP/Air/FEP/Al film (one-layer air bubble structure), and 3) a FEP/Air/FEP/Air/FEP/Al electret film (two-layer air bubble structure) as shown in Fig. 2g. The film with one-layer air bubble structure has the best stability as it maintains about 90% of the initial output energy value after in operations for 20 h under a driving voltage of 20 V at 300 Hz with a preload of 0.7 N. The initial output energy value for all tests is based on the film with one-layer air bubbles and the small degradation is the result of leaked surface charges. The stability of the film with the two-layer air bubble structure is not as good as the film with one-layer air bubble structure because the air bubbles trapped on the top layers may collapse under the preload to result in charge neutralizations (Lower Fig. S13). The FEP-only film has the worst stability as most of the electrostatic charges are on the surface and they could have leaked from external contacts during the haptic sensation tests (Upper Fig. S13).

3.3. Effects of mechanical property

When the volunteer puts his/her fingertip on the actuator patch, a preload is applied as shown in Fig. 3a and a simplified model is developed in Fig. 3b with detailed explanation in Supporting explanation 4 (Knez et al., 2017). In general, the stiffness of the spring structure, the design of the contact structure, and the preload are key parameters affecting the performances. The measured output energy with respect to the stiffness of the spring structure, under a preload of 0.7 N and a
Fig. 5. Actuators array for transmitting patterned haptic information. (a) Optical photo of the $3 \times 3$ actuators array. A1 to A9 mark the locations of 9 actuator pixels. (b) An optical photo showing the haptic communication system based on the actuators array for transmitting patterned information. (b) Schematic diagram of the actuators array transmitting patterned haptic information and the corresponding relationship between specific control signals and patterned information (numbers of ‘0’, ‘1’, ‘2’ and letters of ‘T’, ‘H’ and ‘U’); A: actuator; S: relay switch. (d) The control signal for the relay switch and the driving voltage for the corresponding actuator pixel. An actuator pixel is activated with a driving voltage of 50 V and frequency of 300 Hz. (e) Measured output force by transmitting patterned information of letters of ‘T’, ‘H’, ‘U’ and numbers of ‘0’, ‘1’, ‘2’, under a given preload force of 1 N.

Driving voltage of 20 V at 300 Hz is shown in Fig. 3c. For a spring structure with a stiffness of 1800 N/m under a preload of 0.7 N, a maximal output energy of 0.4 μJ is recorded. For soft actuators with the spring stiffness lower than 1800 N/m, the reduced stiffness results in a more compressed spring structure by the preload, which reduces the output energy as possible electromechanical deformations are suppressed by the preload. On the other hand, for structures with the spring stiffness higher than 1800 N/m, the high stiffness also constrains the electromechanical deformations to result in reduced output energy. As such, it is expected that a specific spring stiffness will have a matching optimal preload value for the largest output energy. The applied actuation frequency also affects the sensational feelings as shown in the measured output energy of the soft actuator with respect to the driving frequency under different preload levels with a fixed spring structure of 1800 N/m in Fig. 3d. It is found that the optimal operation condition is when a preload is 0.7 N under a frequency of 300 Hz to achieve a maximal output energy.

The shape of the contact structure of the soft actuator is also important to generate sensational feelings. Here, a total of 15 volunteers have been tested for prototype soft actuators with flat surface, cone-shape, cylinder-shape with the total contact areas of 2.4, 5.5, 9, and 12 mm², and annulus-shape (with a fixed bump width of 0.5 mm) bumps with the total contact areas of 2.4, 5.5, 9, and 12 mm², as indicated in Fig. 3e and f. In general, actuators with the flat surface or cone-shape bump require higher voltages and frequencies to induce sensational feelings as compared to those of cylinder-shape and annulus-shape structures. Actuators with the annulus-shape bump require the lower applied voltages and frequencies than those of actuators with cylinder-shape bumps with the same contact areas. The annulus-shape structure has a smaller contact area as compared with that of the cylindrical structure of the same radius. Under the same applied voltage, the applied pressure is increased (due to the small area) and the deformation is increased. As such, a lower voltage is required. Furthermore, the “double gradient stimulation effect” from both inner and outer surfaces is designed to induce a large deformation effect on the skin to excite the MC receptors which is sensitive at a bit lower frequency. Under a fixed driving frequency of 300 Hz, an annulus-shape actuator with a contact area of 5.5 mm² achieves the lowest average driving voltage of 4.4 V for inducing the haptic sensation. Under a fixed driving voltage of 20 V, this annulus-shape actuator can produce sensational feeling for a frequency as low as 13 Hz.

3.4. Systematic outputs characterization

As expected, as the driving voltage increases, the output energy and displacement of a prototype soft actuator ($2 \times 2$ cm², preload of 0.7 N, spring stiffness of 1800 N/m, with driving frequencies of 50 and 300 Hz) increase as shown in Fig. 4a. In this case, the output energy/displacement increase from 0.054 μJ/0.015 mm to 0.97 μJ/0.38 mm as the applied voltage increases from 5 to 50 V, respectively. The typical power consumption of the prototype actuator is recorded in Fig. 4b to be 288 μW under a high voltage of 50 V at 300 Hz. In practical applications under an applied voltage of 10 V, the power consumption is only 14 μW. The long-term stability of the actuator patch has been tested for 3 days and the 1-min output energy vs. time data for every 12 h have been recorded for a total of 78 million cycles as shown in Fig. 4c. It is found that the output energy remains stable with small variations of less than 5% in this long-term stability test. On the other hand, even though the actuator is not fully sealed, the 100 μm-thick aluminum electrodes do help reducing moisture penetrations to the electret materials. Experimentally, we have added the output stability study of the actuator under various relative humidity (RH) environments in Fig. S14.
is found the peak outputs of the actuator under RH90% does reduce but still maintain at about 70–80% of that of the same actuator under RH40%.

We also compare the output power density (W/kg) per unit electrical field strength (1 MV/m) of our soft actuator (preload of 0.7 N and driving frequency of 300 Hz) and other state-of-art electroactive polymer actuators with detailed explanations in Table S2 and Supporting explanation 5. As depicted in Fig. 4d, the soft actuator presented in this work has a power density of 3.25 W/kg, which is higher than the P(VDF-TrFE) piezoelectric actuator (2.28 W/kg) and at least one order of magnitude higher than those of dielectric elastomer actuators (DEA) and hydraulically amplified self-healing electrostatic (HASEL) actuators (Ji et al., 2019; Acome et al., 2018; Cheng et al., 2001; Madden et al., 2004; Li and Hashimoto, 2015).

3.5. Haptic communication system based on actuators array

A 3 × 3 actuators array with each pixel size of 2×2 cm² (Fig. 5a) is assembled on a PET substrate for transmitting patterned haptic information. The optical photo and detailed schematic diagram for such a system are shown in Fig. 5b and c, respectively. The randomly selected information with corresponding control signals can wirelessly control the “On” or “Off” of each actuator pixel via 9 relay switches. Here, “1” and “0” signal control the “On” and “Off” for an actuator pixel. In an example, “111010010” control signals mean the A1, A2, A3, A5, and A8 actuator pixels are turned on to transmit haptic pattern of “T". Then, a volunteer touch A1 to A9 actuator pixels in turns to sense the haptic pattern. When an actuator pixel is on, the driving voltage and frequency are 50 V and 300 Hz (Fig. 5d). Under a given preload force of 1 N for each actuator pixel, we measure the array mapping of output force when transmitting patterned information of letters of ‘T’, ‘H’, ‘U’ and numbers of ‘0’, ‘1’, ‘2’. The resolution is high without pixels interference, as shown in Fig. 5e. In Supporting Video 1, a volunteer can accurately sense each random haptic pattern from the actuators array within 10 s, with accuracy rate of 100%. Furthermore, as indicated in Fig. S15, an actuator is coded with Morse code by using short (1.5 s) and long (4 s) full vibration patterns as ‘Dot’ and ‘Dash’, with an interval period of 1.5 s. For example, randomly generated letters of ‘T’ (Dash), ‘H’ (Dot, Dot, Dot, Dot), ‘U’ (Dot, Dot, Dash) have been successfully recognized by a volunteer, with an accuracy rate of 100%, as indicated in the Supporting Video 2.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.bios.2021.113616.

3.6. Untethered wearable operations

The low driving voltage requirement and low power consumption make possible the untethered and long-term operation of the soft actuator with the integration of a flexible battery and circuit board. In this case, the soft actuator is also redesigned and assembled in the form of a fingerstall (Fig. S16). A volunteer can change the bending of the finger to adjust the preload force to have the best sensations for this wearable

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Fig. 6. Untethered system prototype. (a) An optical photo showing an untethered prototype at the fingerstall, together with a flexible circuit and two flexible batteries, and an external wireless control module. The optical photo in upper right shows the wireless control module and the optical photo in lower right shows the front view. (b) Optical photos showing the front and back sides of the flexible circuit. (c) An optical photo showing a typical demonstration of “right” or “left” signals using the untethered system. (d) “Left” and “Right” signals are coded by the 6-V input signal with a working/interval of 1- and 1-s (defined as S) and 8- and 2-s (defined as L) for the signal transmissions, which are converted as the 7.2-V driving signals on the actuator side with a frequency of 300 Hz. A transmission delay time has been recorded in both cases without affecting the recognition results.
As a result, the fingertip length together with flexible circuit/battery are necessary, and flexible Origami paper is used to reduce the discomfort caused by the fingertip. In the future work, fingertip can be replaced by a simple patch to be taped around the finger and the preload can be adjusted by changing the tightness of the tape in the assembly process. The operations are controlled by a wireless control module (Huacheng, Inc. Shenzhen), as illustrated in Fig. 6a and Fig. S17. By using two flexible lithium batteries (Powersteam, PGE0054018, 15 mAH) connected in series, the total applied voltage can reach 7.4 V. This DC voltage is converted into the AC form with a peak value of 5–7.2 V with a frequency between 50 and 300 Hz by a flexible circuit in Fig. 6b. This flexible circuit consists of the signal receiving chip, decoding chip, and signal generating chip (Huacheng, Inc. Shenzhen, Fig. S17). The control signals are received by a loop-antenna and the actuator driving frequency is manually adjusted via the frequency setting connection. Under the driving voltage of 7.2 V and frequency of 300 Hz, the output energy values of the wired and untethered actuator prototypes are very close (Fig. S18), and the stimulation strength can be easily sensed by the fingertip. Since the total power consumption is only about 111.7 mW, this untethered system prototype can operate for around 1 h continuously (Fig. S19).

4. Conclusion and perspective

Thin and soft actuators have been constructed to generate haptic electromechanical stimulations by utilizing the high and stable surface potential of the “air-bubble” polymeric electret film structure together with the appropriate annulus bump design. These soft actuators require driving voltage range of only 5 to 20 V to operate which is significantly lower than those of the state-of-art actuation systems with a large output power density of 3.25 W/kg per unit electric field strength. As a demonstration example, a 3 × 3 actuators array is used for transmitting patterned haptic information, which can be potentially extended to typical areas, such as AR and VR. The integration with flexible battery and circuit board for untethered operations further advances the technology towards practical applications.

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Appendix B. Supplementary data

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