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Untethered Stretchable Displays for Tactile Interaction

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Abstract

Although physical buttons provide tactile sensations that allow them to be identified and pressed without visual focus, their static nature limits their use for dynamic interfaces. Conversely, touchscreens offer highly flexible, task-specific interfaces, but they do not provide the tactile qualities needed for vision-free interaction. Here, we present a stretchable display that can change shape from a flat sheet into a dome when pressurized. The vanishing interface we designed uses hyperelastic light-emitting capacitors (HLECs) that actively emit light, sense strain, and detect finger presses. We characterize the stretch and luminance of the device as the thin sheet is pressurized. Interestingly, but not unexpectedly, these HLEC panels show a pressure-dependent luminance, which we use to highlight where they are being pressed, a visual display of haptic information. We further demonstrate the co-located touch sensing and light-emitting capabilities by developing an interactive memory game.

Keywords: stretchable display, vanishing interface, soft robotics, capacitive sensing

Introduction

The physical buttons and switches found on conventional control panels provide tactile feedback, allowing the user to identify buttons and provide input without shifting visual focus from safety critical tasks such as driving.[1–3] Touchscreen technologies, in contrast, can easily be reconfigured to task-specific interfaces, but their smooth surfaces lack the requisite tactile qualities for nonvisual interaction with machines.[4] To address this gap in technology, many methods have been used to combine the tactile qualities of physical buttons with the reconfigurable nature of digital interfaces. Arrays of independently controlled pneumatic chambers,[5,6] motorized actuators,[7,8] and shape memory alloys[9,10] have all been used to create surfaces that can dynamically change shape. Harrison and Hudson have developed pneumatically actuated laminate structures of translucent elastomers and rigid spacers that enable multiple dynamically changeable physical buttons to occupy the same footprint.[11] These methods, however, require external projection systems to incorporate visual displays into the tactile interfaces as they change shape.

Recent advances in stretchable electronics[12–14] have enabled soft display systems that can undergo large deformations. These stretchable displays are comprised of alternating current electroluminescent phosphors embedded in elastomer membranes and sandwiched between transparent elastomer electrodes.[15–19] These hyperelastic light-emitting capacitors (HLECs) can actively emit light and sense deformation while undergoing areal strains of greater than 635%[17]; using these devices, we have previously reported a color-changing soft robot with extero- and proprioception,[17] as well as higher resolution displays that are capable of displaying multiple colors (R,G,B) and detecting multiple touch inputs.[19]

Here, we present a soft spherical interface comprising HLECs that can actively emit light, sense touch, and, when not in use, vanish into a flat sheet. This *vanishing interface* combines the best traits of physical buttons and electronic touchscreens—the pressurized elastomeric membrane allows tactile interaction while also providing co-located light emission and touch-sensing capabilities. Our HLECs can be pressurized to form physical buttons when and where they are needed (Fig. 1 and Supplementary Video S1), but they vanish into the plane when not in use.

Although previous stretchable electroluminescent devices[17,19] needed to be tethered to a bulky and expensive high-voltage amplifier (610 D; TREK, Inc.) and function generator (3312 A; Hewlett Packard), we now present a standalone, battery-powered electronic system that is capable of delivering a high-frequency ($f \sim 1$ kHz), high-voltage ($V \sim 4$ kV) square wave input signal to illuminate the panels. This compact and portable electronic system senses changes in capacitance and

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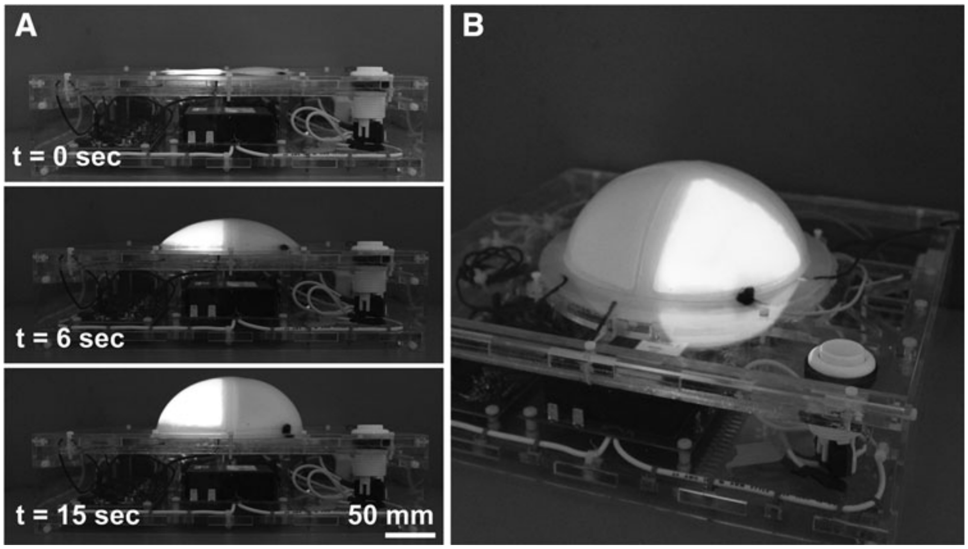

FIG. 1. Four HLECs form an untethered soft interface that is capable of emitting light and sensing touch. **(A)** The membrane is pressurized by using an integrated pump. **(B)** Fully inflated HLEC interface with one panel illuminated by using applied voltage, $V \sim 4\,\text{kV}$, and frequency, $f \sim 1\,\text{kHz}$. HLEC, hyperelastic light-emitting capacitor.

pneumatically inflates a spherical array of four HLECs. To relate these inputs to the physical state of the system, we characterized the stretch and luminance as an unpressurized thin sheet and a pressurized hemisphere. In addition, we found that the HLEC panel light intensity increased during finger pressing locally; we investigated this effect by using image analysis. To demonstrate the utility of all these features, we integrated the core abilities of this system (co-located touch sensing and light emission) into an interactive memory game analogous to the game Simon®.

Materials and Methods

Materials for HLECs

Materials were selected and prepared according to Ref.[17]

Fabrication of HLECs

Molds for each layer of the HLEC were 3D-printed by using an acrylic resin (VeroBlue RGD840, Stratasys Ltd.) with an Objet30 3D printer in glossy mode. The outer encapsulation layers were formed by pouring silicone elastomer (Ecoflex 00-30; Smooth-On, Inc.) directly into these molds and curing for 20 min at 80°C. The relief patterns in these silicone layers served as molds for the hydrogel electrodes. The silicone layers were treated with UV ozone for 10 min before pouring the uncured hydrogel. The hydrogel was cured for 15 s under UV light (320–500 nm, 200 W) (Model S1500; Lumen Dynamics). Each colored panel in the dielectric layer was molded separately by using 3D-printed molds (VeroBlue RGD840, Stratasys Ltd.). After curing for 20 min at 80°C, the four panels were arranged into a circular mold and silicone (Ecoflex 00-30; Smooth-On, Inc.) was poured around the panels to form a dielectric layer with consistent thickness. A thin layer of Ecoflex 00-30 was used to bond all the layers together, forming the stretchable capacitor with a nominal thickness of 5 mm. Carbon conductive grease (846-1P; MG Chemicals) and Cu/Sn plated fabric (Zelt conductive fabric; Mindsets Ltd., United Kingdom) were inserted adjacent to the hydrogel tabs protruding from each electrode. Copper tape was applied to the ends of the conductive fabric to provide compliant electrical connections that could be soldered to copper wire.

Pressure control for stretch and illumination characterization

The HLEC membrane was mounted to a rigid acrylic frame to measure stretch and illumination at controlled pressures. To ensure that the pressurized chamber was airtight, the outer rim of the HLEC interface was glued to the bottom of the acrylic frame with a one-component adhesive (Sil-Poxy, Smooth-On, Inc.). Four screws were tightened around the perimeter to clamp the HLEC membrane between the top and bottom frames. A 150-mm diameter circular cutout in the acrylic constrained inflation to the center of the membrane. The outer rim of the HLEC remained unstrained, ensuring that the hydrogel tabs shown in Figure 2a did not break the electrical connections needed for illumination and capacitive sensing. A port in the bottom of the frame used a barbed fitting and polyethylene tubing (5181K15; McMaster-Carr) to connect the pressure chamber to a regulated pressure source (Performus VI; Nordson EFD). Due to the small tubing (inner diameter, ID $\sim 1.6\,\text{mm}$) and low input pressures ($\Delta P < 10\,\text{kPa}$), we waited at least 30 s between pressure changes for the device to reach steady state before recording measurements.

Capacitive touch sensing

To safely measure capacitance of each HELC panel without damaging any of the electronics, we first isolated the electrodes from the high-voltage supply and connected the top electrode of each HLEC to digital I/O pins on the microcontroller (Arduino Due, SparkFun Electronics). We grounded the illumination control pins, $C_{n,\ illumination}$, for each of the four HLEC panels ($n = \{1,2,3,4\}$) to increase the resistance across the drain-source pathways of the illumination MOSFETs, effectively disconnecting the electrodes from the high-voltage signal (Fig. 3). Subsequently, we set the sensing control pins, $C_{n,\ sensing}$, to high to lower the resistance across the drain-source pathways of the sensing MOSFETs, connecting the hydrogel electrodes to the microcontroller's digital I/O pins. A

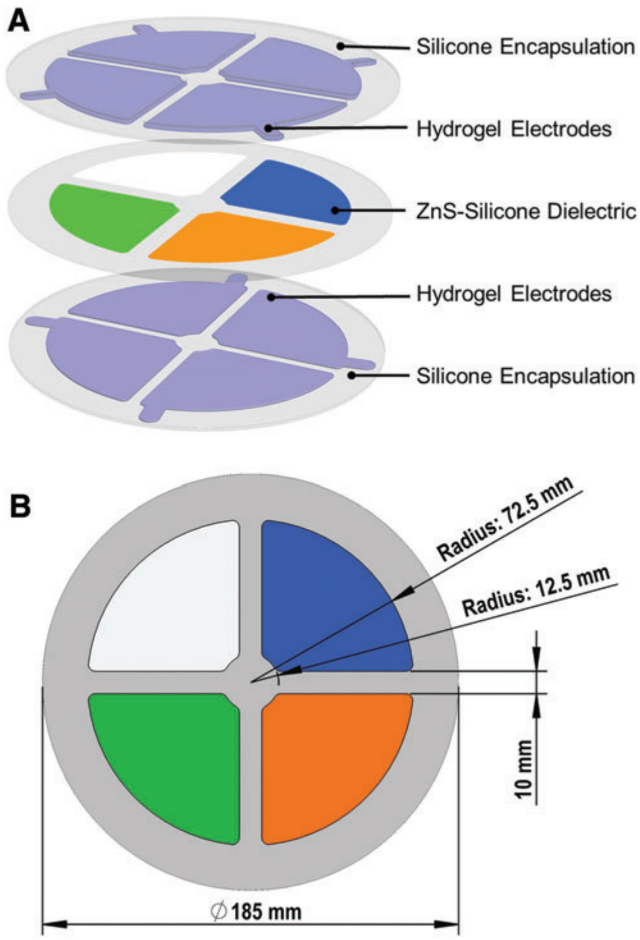

FIG. 2. Design of the elastomeric membrane with four independently controlled HLEC panels. **(A)** Exploded view of the membrane showing its five-layer structure. A 1-mm-thick electroluminescent dielectric layer is sandwiched between hydrogel electrodes, and the device is encapsulated with a final layer of silicone. **(B)** Dimensioned drawing of the dielectric layer. The active area of the device has a 145-mm diameter, with a 20-mm border for mounting. Color images are available online.

resistor ($R = 100\,\mathrm{k\Omega}$) in series with the HLEC electrode forms an RC circuit, where the time constant $\tau = R \cdot C$ correlates to the time delay between state changes in the input and output pins. Because the resistance is nearly constant, this delay is proportional to the capacitance across the electrode—as fingers touch the encapsulating silicone, the effective capacitance increases. We performed a calibration step to account for differences in the absolute capacitance of each panel. One hundred measurements were recorded for each panel without any finger presses. We used the mean of these calibration measurements for each panel to define its initial capacitance, C_0.

Results

Soft interface design

We patterned four different colored and independently controlled HLEC panels into a circular membrane by using replica molding. The center layer of the membrane is composed of an insulating dielectric layer of silicone (Ecoflex 00-30, Smooth-on, Inc.) with embedded ZnS phosphor powders (Global Tungsten & Powders). These phosphors emit light when exposed to a strong electric field ($E \sim 4\,\mathrm{kV/mm}$) alternating with a high frequency ($f \sim 1\,\mathrm{kHz}$); illumination color (orange, green, blue, and white) is dependent on the concentrations of metallic dopants such as Cu and Mn.[20] This central dielectric layer is sandwiched between optically transparent, stretchable electrodes composed of an LiCl polyacrylamide hydrogel that exhibits high mechanical toughness, low volatility, and high ionic conductivity.[21] These active layers are encapsulated within a layer of silicone elastomer (Ecoflex 00-30), allowing the composite device to be safely handled when high voltages are applied. Each of the five layers has a nominal thickness of 1 mm, resulting in a total membrane thickness of ~5 mm. The composite structure and dimensions are shown in Figure 2a and b, respectively.

Control system

To generate the high, alternating electric field required to activate the HLEC panels, we used a regulated high-voltage DC to DC converter (H40P; EMCO) to amplify a 24 VDC input into a 4000 VDC output. A high-voltage MOSFET (IXTT02N450HV; IXYS Corporation) switches this output at a frequency of 1000 Hz to produce a square wave that is capable of causing electron-hole pair recombination in the ZnS phosphors.[20] A pair of MOSFETs switch the connection to the top electrode of each HLEC between the high-voltage signal required for illumination and the low-voltage signal used for sensing capacitance. A 32-bit CortexM3 ARM microcontroller (Arduino Due, SparkFun Electronics) coordinates these operations and records capacitance measurements. A 6800 mAh 12V lithium polymer battery pack powers the entire system, including a 12 VDC pump (D2028, AIRPO) used to pressurize the membrane without the need for an external source of compressed air. The electronic schematic for the pressurization subsystem and a schematic for the illumination and sensory subsystems are shown in Figures 3 and 4, respectively. We used a variant of this control system (Supplementary Fig. S1) to illuminate the HLEC panels shown in Figure 1. To maximize luminance for the device shown in Figure 1, we controlled the top and bottom electrodes with independent, out-of-phase high-voltage signals. For all other presented devices, we used the simplified electronic system shown in Figure 3 to reduce complexity when integrating capacitive sensing.

Stretch characterization and simulation

To characterize extensibility of the membrane, we mounted the composite sheet to a rigid frame as shown in Figure 4. We connected the pressure inlet on the rigid mounting base to a regulated pressure source (Performus VI; Nordson EFD) that is capable of controlling the relatively low pressure ($\Delta P < 10\,\mathrm{kPa}$) needed to fully inflate the membrane. As the membrane was inflated, we measured the change in length of its profile; the resulting stretch ratio ($\lambda = L/L_0$) is included in Figure 5a with intermediate inflation profiles shown in Figure 5b–e. The low elastic modulus of our composite membrane ($E \sim 30\,\mathrm{kPa}$)[22] enables full inflation with a relatively low actuation pressure ($\Delta P \sim 5.5\,\mathrm{kPa}$) as shown in Figure 5e. Although fully inflated, the average stretch along the circumference is $\lambda \sim 1.63$, corresponding to a ~166% increase in area.

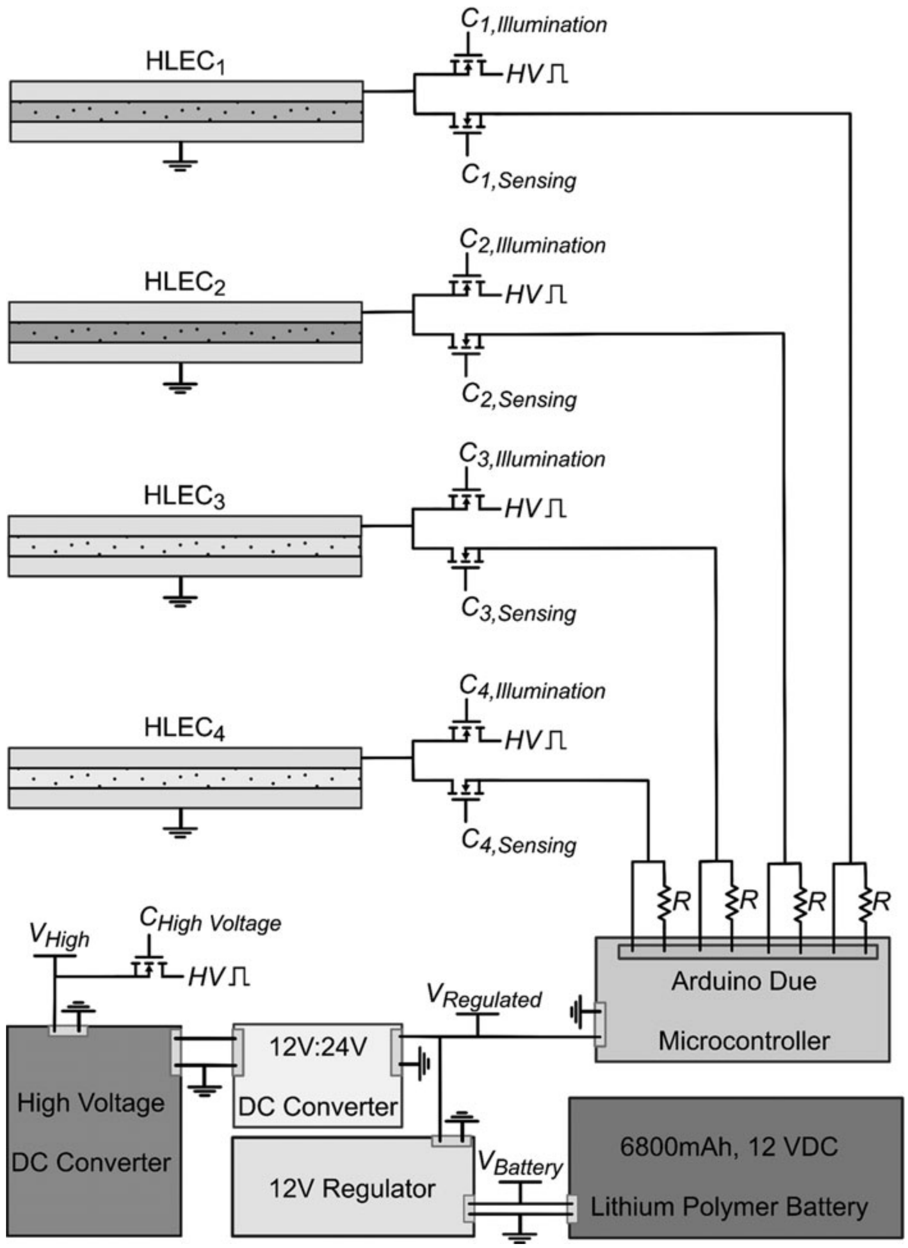

FIG. 3. Electronic design for untethered illumination and touch sensing. One electrode from each HLEC is grounded, whereas the other is switched between a high-voltage square wave for illumination and a low-voltage signal for capacitive touch sensing.

To predict the deformation of our device, we developed an FEM model of the composite membrane by using *Abaqus*™ (DASSAULT Systems). We used uniaxial test data[17] to create a material constitutive model for the HLEC that captures the hyperelastic behavior of the composite structure. This model assumes that the material is isotropic and only experiences plane stresses. We applied the Marlow strain energy potential model to perform the materials curve fit. Due to the large elastic deformations of the HLEC (Fig. 5), the model includes nonlinear geometric effects. The mesh is composed of shell elements with five integration points through the thickness. To compare the FEM model with experimental data, we imposed a fixed boundary condition around the perimeter of the membrane, applied a uniform pressure to the internal surfaces, and recorded the resulting stretch ratio, λ, along the profile. The simulated stretch ratios are shown alongside experimental data in Figure 5a, with a map of vertical displacement, u, overlaid on the inflated profiles in Figure 5b–e. Supplementary Video S2 shows a simulation of the membrane being inflated.

For low pressures ($\Delta P \leq 4.1$ kPa), the mean percent difference between experimental and numerical stretch ratios is 1.24%. At our maximum pressure ($\Delta P \sim 5.5$ kPa), the percent difference between stretch ratios increases to 5.12%. This deviation is due to two limitations of the FEM model: (i) biaxial effects become more significant at higher strains, but the model was created by using data from uniaxial stretch tests; (ii) our device is composed of four HLEC panels framed by thin sections of silicone, but the model assumes the device is isotropic and uses the composite properties throughout. Future research efforts will focus on developing a higher fidelity material model that includes each layer in the composite structure separately for uniaxial and biaxial stretching.

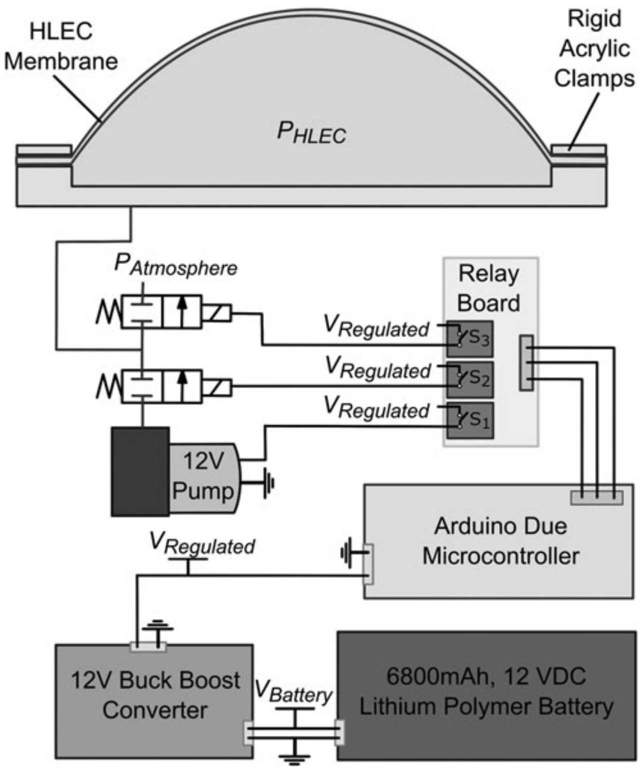

FIG. 4. Pneumatic control system for the untethered HLEC interface. A pair of two-way, normally closed directional valves are used to alternate between inflation by using a 12 VDC pump, holding pressure, and venting to the atmosphere.

Capacitive touch sensing

To enable capacitive touch sensing, we isolated the HLECs from high voltage and connected the top electrode of each HLEC to digital input/output (I/O) pins on the microcontroller; we used the microcontroller to measure the increased capacitance across each electrode when a finger made contact with the surface. By applying a simple threshold to the relative capacitance of each panel, we were able to identify the touched panel throughout all stages of inflation. Figure 6a shows a testing sequence in which we pressed the white, blue, orange, and green panels for three consecutive cycles. We applied this sequence and measured relative capacitance in the unpressurized (Fig. 6b) and pressurized (Fig. 6c) states. Figures 6d and e show the relative capacitance (C/C_0) of each panel during each of these trials. If the relative capacitance of any of the four panels had exceeded a preset threshold (C/C_0 > 2), we identified the panel with the highest relative capacitance as the panel being pressed. The dashed gray line at $C/C_0 = 2$ in Figure 6b and d shows the threshold for detection; the gray, blue, orange, and green boxes below the data represent the identified buttons. Fluctuations in the duration of each signal are due to manual timing used for pressing all four panels in sequence. Although more noise is present in the pressurized state, we were still able to correctly detect the pressed panel in all cases. In some cases, the relative capacitance of panels adjacent to the finger press exceeded the detection threshold, but the increase in capacitance was always highest for the panel being directly pressed.

Illumination

As the HLECs are capacitive, their deformation affects the electric field between parallel electrodes: The applied voltage, V, and the dielectric thickness, t, determine the field strength, $E = V/t$ (Equation 1). In addition, the elastomers comprising the HLEC membrane can be treated as incompressible and, thus, we can relate the axial, λ_1, transverse, λ_2, and out-of-plane, λ_3, deformations to one another as $\lambda_1\lambda_2\lambda_3 = 1$. Therefore, as the thickness, $t = \lambda_3 t_0$ (Equation 2), decreases, the area, $A = A_0\lambda_1\lambda_2$ (Equation 3), of the membrane increases. Combining Equations (1–3), we define the field strength across the dielectric layer in terms of the voltage, area, and initial dimensions of the HLEC membrane: $E = (VA)/(A_0 t_0)$. As the light emission from the HLEC is electric field driven, we can modulate the local intensity simply by changing the dimensions of the panel.

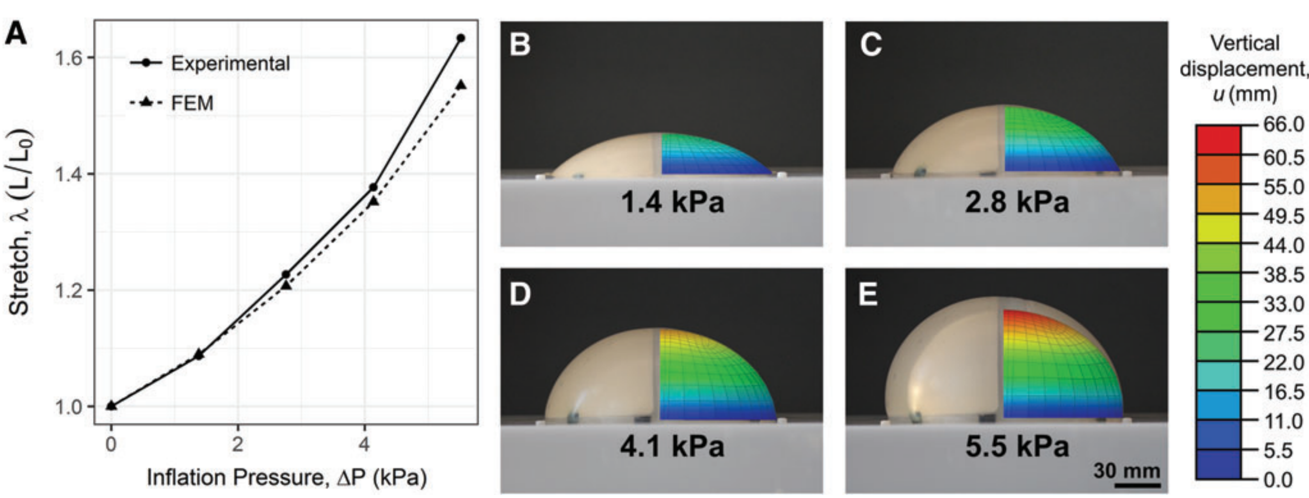

FIG. 5. Stretch of the elastomeric membrane during inflation. **(A)** Aggregate stretch across the profile of the HLEC membrane as internal pressure is applied. Experimental results are compared with results of a numerical simulation. Profiles of the device are shown alongside vertical displacement, u, for pressures of 1.4 kPa **(B)**, 2.8 kPa **(C)**, 4.1 kPa **(D)**, and 5.5 kPa **(E)**. Color images are available online.

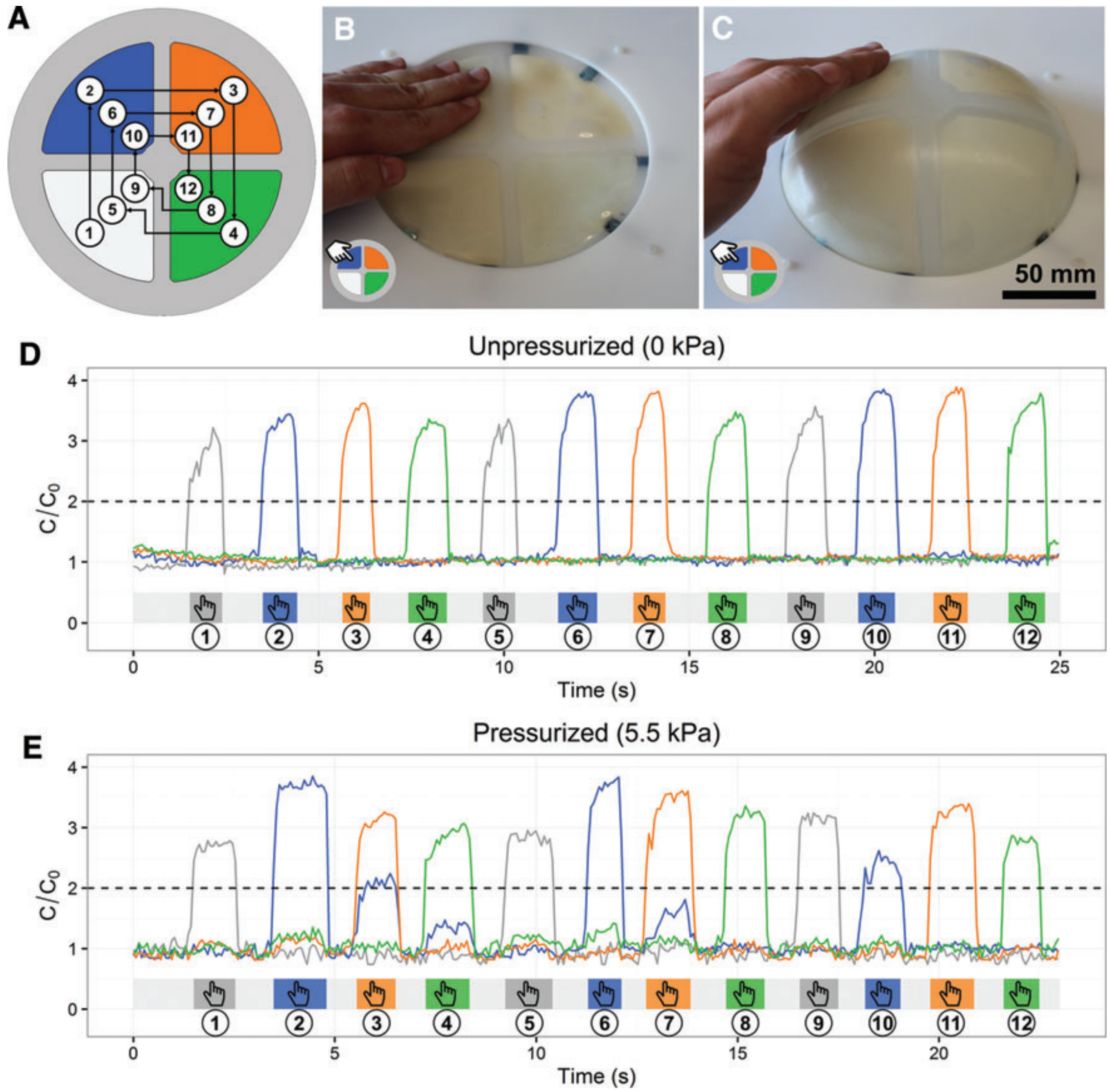

FIG. 6. Touch-sensing capabilities of the HLEC panels. **(A)** Sequence of touches to the HLEC panels, starting with the *white panel* in the *bottom left* and proceeding clockwise around the device. A sequence of 12 touches (three per panel) is repeated for the unpressurized and pressurized states. **(B)** Representative touch on the *blue panel* in the unpressurized state. **(C)** Representative touch on the *blue panel* in the pressurized state. **(D)** Relative capacitance for each HLEC panel as it is pressed in the unpressurized state. **(E)** Relative capacitance for each HLEC panel as it is pressed in the pressurized state. The *dashed gray lines* in **(D)** and **(E)** indicate the threshold used to indicate whether a panel has been pressed. The *colored rectangles* below the capacitance data represent which panel, if any, has been identified as being pressed. Color images are available online.

When we hold the amplitude and frequency of the voltage source constant and stretch the HLEC, the luminance increases. Figure 7a shows the luminance of the blue panel as the HLEC inflates. To measure this increase, we used a luminance meter (SM208; M&A Instruments) to collect three measurements at each of the pressures set by an external pressure regulator (Performus VI; Nordson EFD). We pressed the luminance meter against the surface of each panel to ensure that ambient light, the changing area of the illuminated panel, and the distance to the meter did not affect our measurements. Throughout an inflation cycle, the luminance of the blue panel increased 354% from 3.47 ± 0.53 to 15.74 ± 0.72 cd/m^2 as the panel stretched due to the applied pressure (Fig. 7a).

Figures 7b and c and Supplementary Video S3 show the anisotropic change in luminance of the single blue panel as a finger deforms the HLEC. We used the MATLAB image processing toolbox to analyze individual frames from a recorded video and to determine the relative luminance across the panel. For this task, we first converted the native RGB color space of each image to a YCbCr color space where the three components for each pixel represented relative luminance (Y) and chrominance (Cb and Cr) color values. We then isolated the illuminated region of interest by applying a color-based threshold. For this region of interest, we generated a heat map based on the relative luminance component, with brighter areas shown in yellow and darker areas shown in red. The localized increase in luminance as a finger press deforms the panel becomes more pronounced as the finger presses deeper into the membrane.

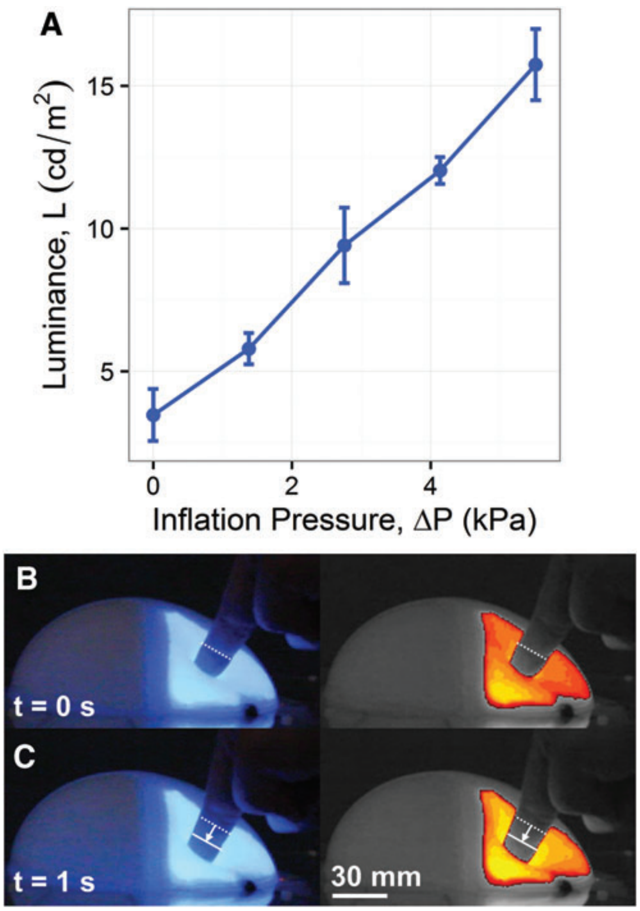

FIG. 7. Change in luminance during deformation. **(A)** Luminance for the *blue panel* as the membrane is pressurized. Error bars represent the standard error calculated by using three measurements. **(B, C)** Pressurized HLEC panel being deformed with a finger press while illuminated. The images on the *right* show the relative luminance of the device, with *yellow* coloration corresponding to the highest luminance. Color images are available online.

Gameplay

Finally, we integrated the sensory and illumination capabilities to create an interactive memory game analogous to the Hasbro game Simon. To play the game, the player must repeat a given sequence of illuminated panels in the correct order. After the illumination cycle is complete, the capacitive touch sensors detect whether the player has selected the next panel in the sequence. If the player correctly selects all panels in the sequence, the game adds a randomly generated panel to the sequence and the process is repeated. If the player selects the wrong panel or waits too long to provide an input, flashing HLEC panels indicate that the game has ended (Supplementary Video S4 shows a representative game). In this example, the gameplay lasted for nearly 3 min and the player reached a sequence of 13 panels before making an error and ending the game. The four different colored panels used for gameplay are shown illuminated in their unpressurized (Fig. 8a–d) and pressurized states (Fig. 8e–h); Supplementary Video S5 shows a finger deforming the illuminated panels.

To determine the power consumption of our interface, we substituted the lithium polymer battery shown in Figures 3 and 4 with a switching DC bench power supply (1550; BK Precision). With a 12 VDC input, we measured a baseline current of 1.04 A that increases to 1.56 A when a panel is illuminated. For a typical game, panels are illuminated ∼29% of the time, leading to an average power consumption of 14.3 W. Based on these power requirements, we estimate that our 6800 mAh will provide ∼5.7 h of gameplay on a single charge.

Discussion

In this article, we present a portable, battery-powered electronic control system for HLECs. This portable system stores the HLEC as a flat sheet when not in use and inflates the membrane into a hemisphere for use as a tactile interface. To understand the relationship between physical system states and measurable electrical signals, we characterized the stretch and luminance of the membrane at varying levels of internal pressurization. For sensing touch, we implemented a capacitive

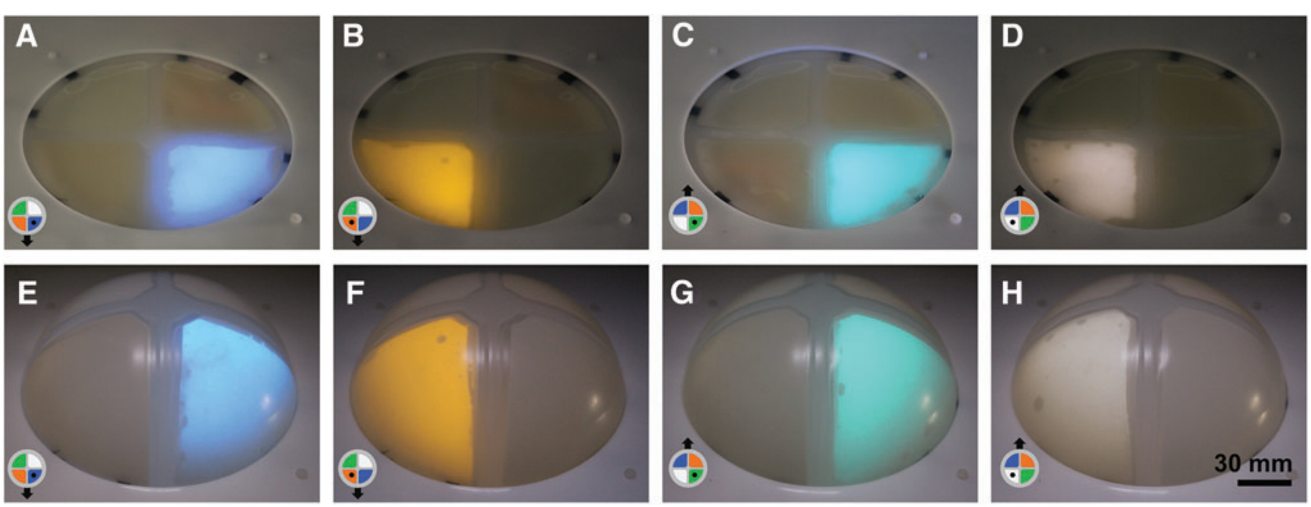

FIG. 8. Illumination of the HLEC panels. *Blue* **(A)**, *orange* **(B)**, *green* **(C)**, and *white* **(D)** panels are illuminated whereas the membrane is uninflated. *Blue* **(E)**, *orange* **(F)**, *green* **(G)**, and *white* **(H)** panels are illuminated whereas the membrane is pressurized to ∼4.1 kPa. Color images are available online.

sensing method that decouples touch from deformation, and we used this method to detect button presses by using simple thresholding of relative capacitance. Through integration of the HLEC array into a soft version of the game Simon, we demonstrated the combined utility of illumination and touch sensing.

Although a 1-mm-thick silicone encapsulation layer allowed us to safely interact with our device while a high voltage, $V \sim 4\,kV$, was applied, our system could be improved with a more refined architecture. Since the embedded electroluminescent phosphors are driven by the electric field strength, a thinner dielectric layer would provide the same luminance with a lower applied voltage. A lower voltage requirement would enable more applications for human–robot interaction by simplifying the drive electronics and reducing power consumption. More advanced fabrication techniques can be used to increase the resolution of the interface. Already, Li *et al.* have developed the use of photopatterning and transfer printing to develop mm-scale HLECs arranged in an array of 64 individually addressable pixels.[19] Combining these improvements with more complex pneumatic networks, we envision a general-purpose interface that provides flexibility in both visual display and three-dimensional shape.

Acknowledgments

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Author Contributions

B.P. designed the control system, designed the experiments, conducted the experiments, analyzed the data, and wrote the article; S.L. fabricated the HLECs and edited the article; C.L. conducted the experiments and edited the article; J.C. designed electronics to illuminate the HLEC; E.H. modeled the stretch of the pressurized HLEC and wrote the article; and R.S. initiated the concept, designed the experiments, supervised the experiments, and edited the article. Contact R.S. for any questions regarding experimental raw data and design schematics.

Author Disclosure Statement

The fabrication method for HLECs presented in this work has been filed under a PCT patent application, No. PCT/US16/60346, for Stretchable Electroluminescent Devices and Methods of Making and Using the Same. The listed inventors are C.L., S.L., B.P., S.R., and R.S.

References

1. Burnett G, Lawson G, Millen L, *et al.* Designing touchpad user-interfaces for vehicles: Which tasks are most suitable? Behav Inf Technol 2011;30:403–414.
2. Chiang DP, Brooks AM, Weir DH. On the highway measures of driver glance behavior with an example automobile navigation system. Appl Ergon 2004;35:215–223.
3. Poupyrev I, Maruyama S, Rekimoto J. Ambient Touch: Designing Tactile Interfaces for Handheld Devices. Proceedings of the 15th Annual ACM Symposium on User Interface Software and Technology—UIST '02, 2002:51–60.
4. Vinot JL, Letondal C, Pauchet S, *et al.* Could tangibility improve the safety of touch-based Interaction? Int Conf Hum Comp Inter Aeros 2016;8:1–8.
5. Mosadegh B, Mazzeo AD, Shepherd RF, *et al.* Control of soft machines using actuators operated by a Braille display. Lab Chip 2014;14:189–199.
6. Stanley A, Okamura A. Controllable surface haptics via particle jamming and pnuematics. IEEE Trans Haptics 2015; 8:20–30.
7. Leithinger D, Follmer S, Olwal A, *et al.* Shape displays: Spatial interaction with dynamic physical form. IEEE Comp Graph Appl 2015;35:5–11.
8. Iwata H, Yano H, Nakaizumi F, *et al.* Project FEELEX: Adding haptic surface to graphics. Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques—SIGGRAPH '01, 2001:469–476.
9. Poupyrev I, Nashida T, Maruyama S, *et al.* Lumen: Interactive visual and shape display for calm computing. ACM SIGGRAPH 2004 Emerging Technologies—SIGGRAPH '04, 2004:17.
10. Nakatani M, Kajimoto H, Vlack K, *et al.* Control method for a 3D form display with coil-type shape memory alloy. Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005:1332–1337.
11. Harrison C, Hudson SE. Providing dynamically changeable physical buttons on a visual display. Proceedings of the 27th International Conference on Human Factors in Computing Systems—CHI 09, 2009:299–308.
12. Rogers JA, Someya T, Huang Y. Materials and mechanics for stretchable electronics. Science 2010;327:1603–1607.
13. Keplinger C, Sun JY, Foo CC, *et al.* Stretchable, transparent, ionic conductors. Science 2013;341:984–987.
14. Sun JY, Keplinger C, Whitesides GM, *et al.* Ionic skin. Adv Mater 2014;26:7608–7614.
15. Wang J, Yan C, Jianzhi Chee K, *et al.* Highly stretchable and self-deformable alternating current electroluminescent devices. Adv Mater 2015;27:2876–2882.
16. Wang J, Yan C, Cai G, *et al.* Extremely stretchable electroluminescent devices with ionic conductors. Adv Mater 2015;28:4490–4496.
17. Larson C, Peele B, Li S, *et al.* Highly stretchable electroluminescent skin for optical signaling and tactile sensing. Science 2016;351:1071–1074.
18. Stauffer F, Tybrandt K. Bright stretchable alternating current electroluminescent displays based on high permittivity composites. Adv Mater 2016;28:7200–7203.
19. Li S, Peele BN, Larson CM, *et al.* A stretchable multicolor display and touch interface using photopatterning and transfer printing. Adv Mater 2016;28:9770–9775.
20. Kitai A. Luminescent Materials and Applications. Chichester, England: John Wiley, 2008: 249–268.
21. Bai Y, Chen B, Xiang F, *et al.* Transparent hydrogel with enhanced water retention capacity by introducing highly hydratable salt. Appl Phys Lett 2014;105:151903.
22. Shepherd RF, Stokes AA, Nunes RMD, *et al.* Soft machines that are resistant to puncture and that self seal. Adv Mater 2013;25:6709–6713.

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