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An integrated electronic textile system capable of displaying full-color images and videos

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ABSTRACT **Smart electronic textiles with electronic functions like displaying can provide transformative opportunities for wearable devices that traditional rigid devices are hard to realize. A general strategy of enabling textiles to display is weaving light-emitting fibers into textiles and designing control circuits. However, it remains challenging for the current electronic textiles to display full-color images and videos. Here, we demonstrate a large-area integrated electronic textile system (with a size of 72 cm × 50 cm) by weaving light-emitting diode (LED) fibers, touch-sensing fibers and polyester fibers, which could display full-color images (with a gamut of 117.6% NTSC) and continuous videos (with a refresh rate of 11.7 Hz) by designing low-voltage supply mode and parallelly transmitting circuits. After integration of touch-sensing fibers, such textile system could achieve various touch display and interactive functions like smart phones or computers, including hand input of text, hand painting, computing and playing games. The stability and durability of textile system withstanding 5000 bending cycles was also demonstrated for wearable applications. The integrated electronic textile system shows similar flexibility and breathability with regular textiles, which is promising to serve as new human-machine interface to change the way in which people interact with electronics.**

Keywords: electronic textile, display, refresh rate, integration system

INTRODUCTION

With the rise of new information technologies such as 5G and Internet of Things [1], wearable devices are regarded as the next-generation electronics after computers and smart phones [2–4]. Among them, smart electronic textiles possess the same flexibility and breathability as regular clothing [5], thus can effectively meet the flexible, lightweight, and comfortable requirements of wearable devices [6–8]. After integration with electronic functions like displaying [9], sensing [10–12], information processing [13,14] and power supplying [15,16], electronic textiles are promising for a series of interdisciplinary applications [17] where traditional plane or bulky devices may struggle [18,19]. For instance, current small-size wearable devices can be replaced with large-area electronic textiles to seamlessly fit irregular and soft human bodies [20,21], and the mobile phones or computers may even be revolutionized from rigid panels to soft textiles. As the main output terminal of electronic devices, integrating displays into textiles is one of the most crucial demands for efficient information interaction, but which still faces challenges in displaying color image and dynamic videos [22].

A general and effect strategy of enabling electronic textiles to display is directly weaving light-emitting fibers into textiles with certain patterns [23,24]. The displaying function can be then realized by designing control circuits according to the weaving patterns of light-emitting fibers [25,26]. The most common light-emitting fibers are fabricated based on alternating current electroluminescence materials like ZnS phosphors [27,28], because they are suitable for solution processing and possess high stability for complex working environments [29]. Unfortunately, the above electronic textiles can display very limited patterns only by controlling on/off of whole light-emitting fiber, making it hard to realize dynamic pixel images/videos for efficient information interactions [30]. Moreover, such electronic textiles have also been hindered by the issues of simple color and high driving voltage [31]. As an alternative to light-emitting fibers [32–34], the electronic textile woven with light-emitting diode (LED) fibers [35,36] has the potential to display color images by independently controlling three-primary-color LEDs. However, only simple word and cartoon patterns have been initially realized in the electronic textile woven with LED fibers [37], it remains challenging to display real color images and continuous videos through efficient controls of large amounts of dynamic LED pixels with high refresh rate [38].

Here, we report an integrated electronic textile system that can display full-color images and videos with a refresh rate of >10 Hz. A large-area electronic textile system with a size of 72 cm × 50 cm was obtained by weaving LED fibers, touch-sensing fibers and polyester fibers into textile. By designing power supply mode of step voltage drop and parallelly transmitting circuit, the textile system containing 4.32×10^4 LEDs was driven to display color images and videos under a low voltage. By further integrating touch-sensing fibers with the LED fibers, the textile system could achieve various touch display functions for efficient human-computer interactions. Besides displaying images and videos, the integrated electronic textile system could realize various interaction applications like smart phones and computers, including hand input of text, hand

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painting, computing and playing touch games.

EXPERIMENTAL SECTION

Fabrication of the LED fiber

The RGB LED fiber was fabricated based on the insulating polyimide substrate with a width of 50 cm and thickness of 200 μm (Fig. S3). A copper film with adhesive layer was firstly coated on the polyimide substrate. Then, the circuit pattern was acquired by photoetching. A cover film was coated to protect the circuit. The RGB LEDs were then placed on the substrate through surface mounting and reflow soldering techniques. A 104-nF capacitor was parallelly placed with an interval of ten RGB LEDs to prevent voltage overshoot. Finally, the substrate was cut into fibers with a width of 4 mm and encapsulated with polymer tubes.

Fabrication of touch-sensing fiber

The touch-sensing fiber was fabricated on the insulating polyimide substrate with a width of 50 cm and thickness of 200 μm (Fig. S14). A copper film with adhesive layer was firstly coated on the polyimide substrate. Then, the circuit pattern was acquired by photoetching. A cover film was coated to protect the circuit. A resistance (10 Ω) was then placed on the substrate by surface mounting and reflow soldering technologies. A resistance of 10 kΩ was connected between analog-to-digital converter (ADC) input port and direct current (DC) (+) port. Finally, the substrate was cut into fibers with a width of 4 mm.

Weaving process of textile system

The integrated textile system was fabricated by weaving together LED fibers, touch-sensing fibers and polyester fibers. One touch-sensing fiber was attached on the reverse side with intervals of every four LED fibers. Eight (2 × 4) RGB LED pixels were controlled by one touch-sensing bottom. The weaving process was conducted on a GT6012 multi-arm loom with a breadth of 2 m (Hangzhou Textile Machinery Accessories Factory). The polyester fibers passed through the heddles as the warps. Then, the LED fibers and touch-sensing fibers were successively crossed the warps manually after each shedding. The beating-up process was conducted manually to avoid the damage of LED fibers. The LED fibers were divided into 6 groups (each group contained 2 subgroups). The data lines, power lines and ground lines were connected in a zig-zag route in each subgroup. The touch-sensing fibers were divided in to 9 groups, each containing 200 touch points. The power lines and the ADC input lines were connected in a zig-zag route in each group. The data (in) ports of each subgroup of LED fiber and the ADC input ports of each group of touch-sensing fiber were connected to the individual input/output (I/O) port of the singlechip. The power lines of the LED fibers and touch-sensing fibers were connected to the DC step-down module.

Driving methods

The power was supplied by a switching power (S-1500-36, Li Chengan), which converts civil electricity (220 V alternating current (AC) power) in to 36 V DC power. Then, the 36 V DC power was converted into 5 V DC power through a direct current step-down module purchased from Diymore. A singlechip microcomputer development board (STM32H743, Zhengdianyuanzi) was selected as the control unit. The program was coded by Keil. For displaying function, the data transmitted through the individual I/O port of singlechip in parallel. The data in each subgroup transmitted in a zig-zag route. When the touch-sensing fiber was pressed, the returned ADC value will be converted into the coordinates of the touch points. Thus, the corresponding order was conducted such as the new image was displayed by LED fibers. All the data was stored in the singlechip microcomputer. The sensors such as thermometer and illuminometer were connected to the individual I/O port with ADC module. The measured physical quantities were converted to the analog quantities by the sensors and then were converted to the digital quantities by ADC module.

RESULTS AND DISCUSSION

The electronic textile system was fabricated by weaving LED fibers, touch-sensing fibers and polyester fibers together (Fig. 1a), where the LED and touch-sensing fibers function as wefts, while polyester fibers function as warps. The weaving process was conducted through a multi-arm loom with a breadth of 2 m (Fig. S1). During the weaving process, the touch-sensing fiber was placed on the reverse side of each LED fiber to ensure precise control of LED pixels (Fig. S2). The coordinates of the LED fibers and touch-sensing fibers were mutually corresponding to each other. To endow the electronic textile system with touch displaying function, the touch-sensing fibers input coordinates to a singlechip, which then output the data to the LED fibers. As shown in Fig. 1b, an integrated textile system with a size of 72 cm × 50 cm was fabricated by weaving LED fibers with a total length of 72 m (containing 4.32×10^4 LEDs), which could display color images of touch-control applications (Apps) like smart phones. The resultant textile system was highly flexible and breathable (Fig. 1c), which could normally work under complex deformations like bending and even folding.

The LED fiber woven in the textile was the basic building block to achieve displaying function (Fig. 2a, b), which was typically prepared by imparting RGB LEDs and driving module on the polyimide stripe printed with connecting circuit (Fig. S3) [39]. Three bonding pads were placed between each individual RGB LED. Thus, each individual RGB LED can be replaced once it is broken. Specifically, an individual RGB LED had four ports: data-in port, data-out port, DC port and ground port (Fig. 2c). The LED fiber was obtained after connecting data-out port of one RGB LED with the data-in port of the adjacent one. The resultant LED fiber thus had three ports: DC port, data port and ground port (Fig. 2d). Unless otherwise stated, the width of the LED fiber was 4 mm, and the distance between the individual LEDs (pixel distance) was 5 mm (Fig. S4). To further simplify the electrical connection, the data ports of the LED fibers were connected with each other using one data line in a zig-zag route to drive the textile system for displaying (Fig. 2e).

Aiming for displaying of textile system with a large area, the internal resistance of the data and power lines was a serious issue that needs to be addressed, which could cause obvious voltage drop to dramatically weaken the luminescent performances of LED fibers. For instance, the length of the power line was 144 m in the as-prepared textile system. The LEDs in the fiber can produce uniform brightness when the driving voltage was between 3.7 and 5.5 V. However, the voltage would drop to less than 3.7 V as the length exceeded 3 m, which was difficult to power the LEDs and caused color distortion. To solve above problem, we designed a step-voltage-drop mode to ensure the

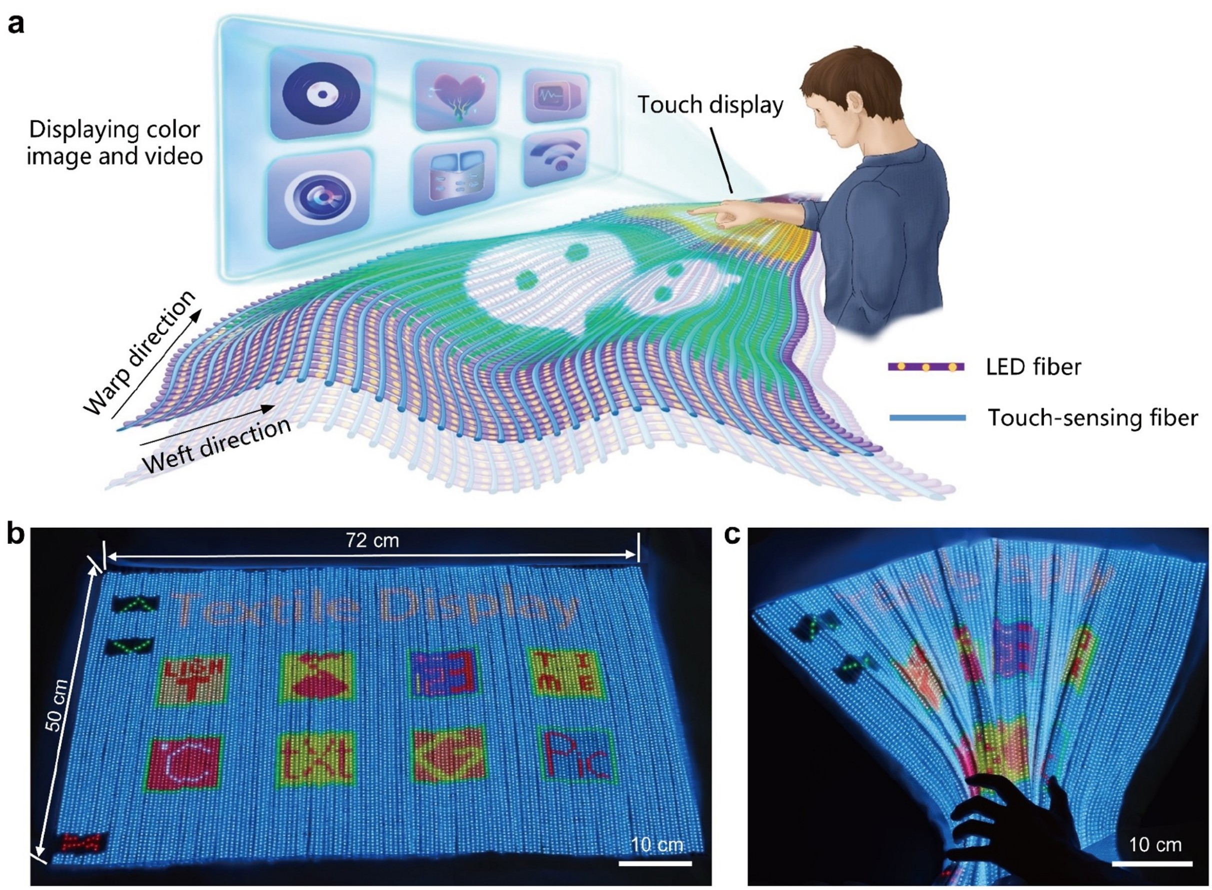

Figure 1 Schematic diagram and photographs of the integrated electronic textile system. (a) Schematic diagram of the integrated electronic textile system. (b) Photographs of the integrated electronic textile system. (c) Photographs of integrated electronic textile system working under bending and folding deformations.

normal displaying of electronic textile system (Fig. 2f). Specifically, the 14,400 (144 × 100 × RGB) LEDs were divided into 12 groups, in which each group contained 1200 (12 × 100 × RGB) LEDs. The power lines were connected at both ends of each group. The applied voltage of the displaying textile was chosen as a relatively high value of 36 V to decrease the current in the power line, thus reducing the voltage drop. The actual driving voltage on the RGB LEDs at each group was 5 V by using a direct current step-down module. As a result, the maximum applied current of each group was 4.5 A (Fig. S5), which could effectively satisfy the power requirements of the RGB LEDs for normal light emission (Fig. 2g). The illuminance of the electronic textile containing 400 RGB LEDs could reach 5439 lx (Fig. S6), which is comparable with that of typical commercial displays. The voltage drop in the data line was less than 0.5 V, thus ensuring the precise data transmission (Fig. 2h). The full-color display of the textile system was achieved through light mixing of primary colors in the RGB LED unit, where the brightness of the red, green, and blue light had been precisely tuned by the driving microchip in the LED fibers (Fig. S7). As a result, each primary color exhibited 255 grades of brightness level, which enabled the textile system to achieve full-color display with a gamut of 166% sRGB or 117.6% NTSC (Fig. 2i).

Realizing dynamic pixel display (such as displaying videos) is another unmet need for current electronic textile system. To enable textile system to display continuous color video, the time interval between the frame images (refresh time) should be less than 100 ms. However, the total data transmission time for the large-area electronic textile system was more than 300 ms due to the large number of LEDs. To address this issue, the data ports of the LED fibers were divided into 6 groups (containing 2 subgroups, and 1200 RGB LEDs in each subgroup), in which the data was parallelly transmitted (Fig. 3a). The data in each subgroup was transmitted successively. To avoid the fluctuations of the voltage and the disturbance of each group, a capacitance of 104 nF was connected between the data port and ground port of each LED fiber. As a result, there are 64 (2^6) cases of data situation, and each group of data was transmitted individually without crosstalk (Fig. 3d, Figs S10, S11). Considering the balance of refresh rate and the number of the data cases, 6 groups of data were sent in parallel. Among them, the individual RGB LED was controlled by 24-bit data (8 bit for each red, green and blue LED unit), and each bit data consisted of '1' or '0' codes. The '1' code represented high-level input voltage with a continuous time of 900 ns ± 100 ns and low-level input voltage with a continuous time of 300 ns ± 100 ns, while the '0' code represented high-level input voltage with a continuous time of 300 ns ± 100 ns and low-level input voltage with a continuous time of 900 ns ± 100 ns (Fig. 3c and Fig. S8). A reset code with a low-level input voltage (with a duration time of over 200 μs) was further added between two frame images (Fig. S9). As the data was divided to 6 groups (containing 2 subgroups with data transmission in serial) and

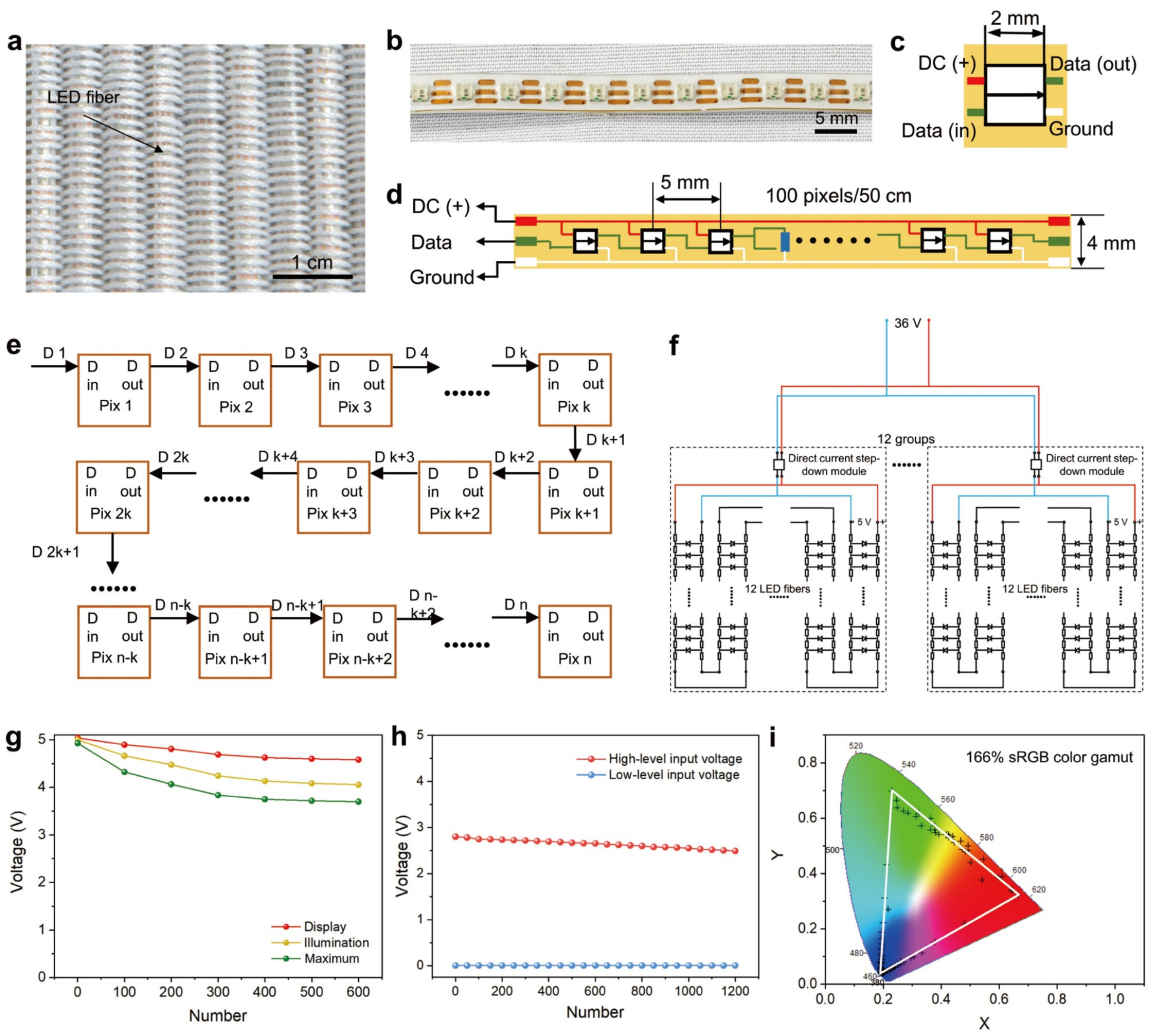

Figure 2 Design of the display module in the integrated textile system. (a) Photograph of the textile system woven with LED fibers. (b) Photograph of a LED fiber. (c) Schematic diagram of a RGB LED. (d) Schematic diagram of the LED fiber. (e) Schematic diagram of zig-zag route for data transmission. Schematic diagram of RGB LEDs. "*n*" and "*k*" represent the total number of RGB LEDs and the number of RGB LEDs in a row, respectively. (f) Schematic diagram of the strategy of step-voltage-drop mode. (g) The tested voltage of the power line with the increasing numbers of RGB LEDs. (h) The tested voltages of the data line with the increasing numbers of RGB LEDs. (i) The color gamut range of the integrated textile system.

transmitted in parallel (Fig. S12), the refresh time of each frame was calculated as $2 \times 1200 \times 24 \times 0.0012 = 69.12$ ms. According to the theoretical calculation, the refresh time would be decreased to less than 100 ms (Fig. 3b) even after adding the data decoding time (less than 30 ms). The actual refresh time (the time interval of each frame image) measured by oscilloscope was 93 ms, consisting of 64 ms of data transmitting time (32 ms for each subgroup) and 29 ms of data decoding time (Fig. 3e). The experiment result agreed well with the theoretical calculation. The resultant textile system could display 60 frames of color images in 5.14 s (with a refresh frequency of 11.7 Hz), thus enabled to play continuous videos (Fig. 3f, Video S1).

To endow the textile system with touch control function for convenient interaction experience like smart phones and computers, the touch-sensing fibers were woven on the reverse side of LED fibers (Fig. S13). The touch-sensing fiber was fabricated by imparting resistances and buttons on the polyimide stripe printed with driving circuits (Fig. S14), which contained four ports: DC (+) port, ground port and two ADC input ports (Fig. S15). The distance between the buttons was designed as 1 cm to well match the size of fingers, and the width (4 mm) of the touch-sensing fiber was similar to that of LED fiber. As shown in the Fig. 4a, eight (2×4) RGB LED pixels were controlled by one touch-sensing bottom (point). The ADC input lines and power lines were connected in a zig-zag route to reduce the length of conductive path (Fig. S16). According to the voltage divide principle, the voltage and the touch position at the ADC input line followed one-to-one correspondence. By converting analog value (voltage) to digital value, the position on the touch-sensing fiber could be identified. When the touch-sensing button was

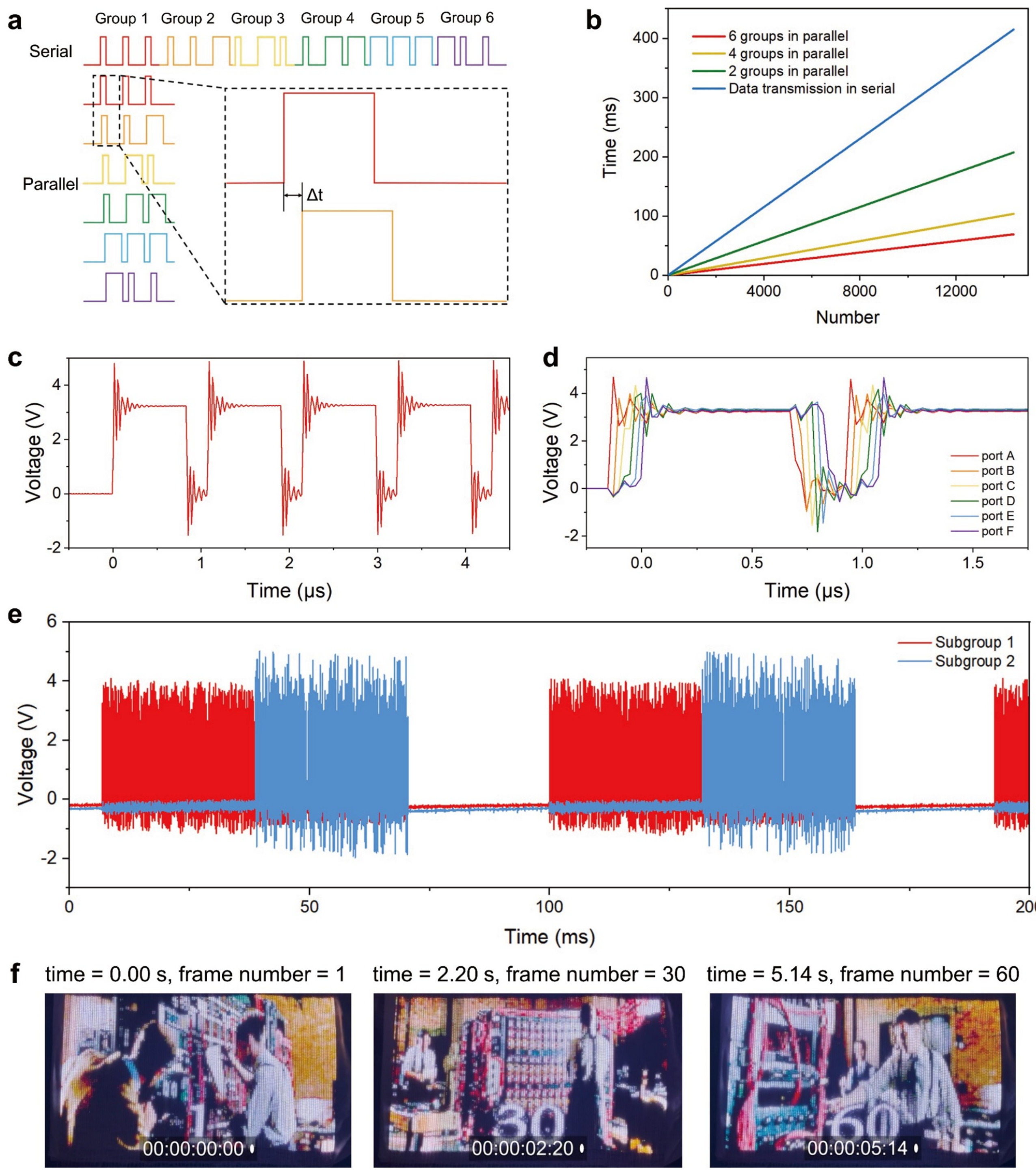

Figure 3 Data transmission of electronic textile system for displaying. (a) Schematic diagram of the data transmission of LED fiber in serial and in parallel. Δt represents the period of the chip in the driver. (b) Theoretical calculation of the refresh time at different numbers of LED fiber groups in parallel. (c) The input voltage level of '1' code measured by oscilloscope. (d) Tested input voltage levels of '111111' code when the data were transmitted by 6 groups in parallel. (e) Tested refresh time when playing a video. The refresh time is less than 100 ms. (f) Photographs of the frame images from the video at different time.

not pressed, the ADC input port was in a float state, which would return a random value. To avoid the occurrence of random value, a resistance (R_0) with much higher than that of imparted resistance was connected between DC (+) and ADC input ports. The value R_0 was much lower than the internal resistance of ADC module. R_0 was finally chosen as 10 kΩ. According to the voltage division theory, the ADC value (A) can be calculated by Equation (1) as following,

$$A = N \times \frac{n-k}{\frac{1}{1/k - R/R_0} + n - k}, \quad (1)$$

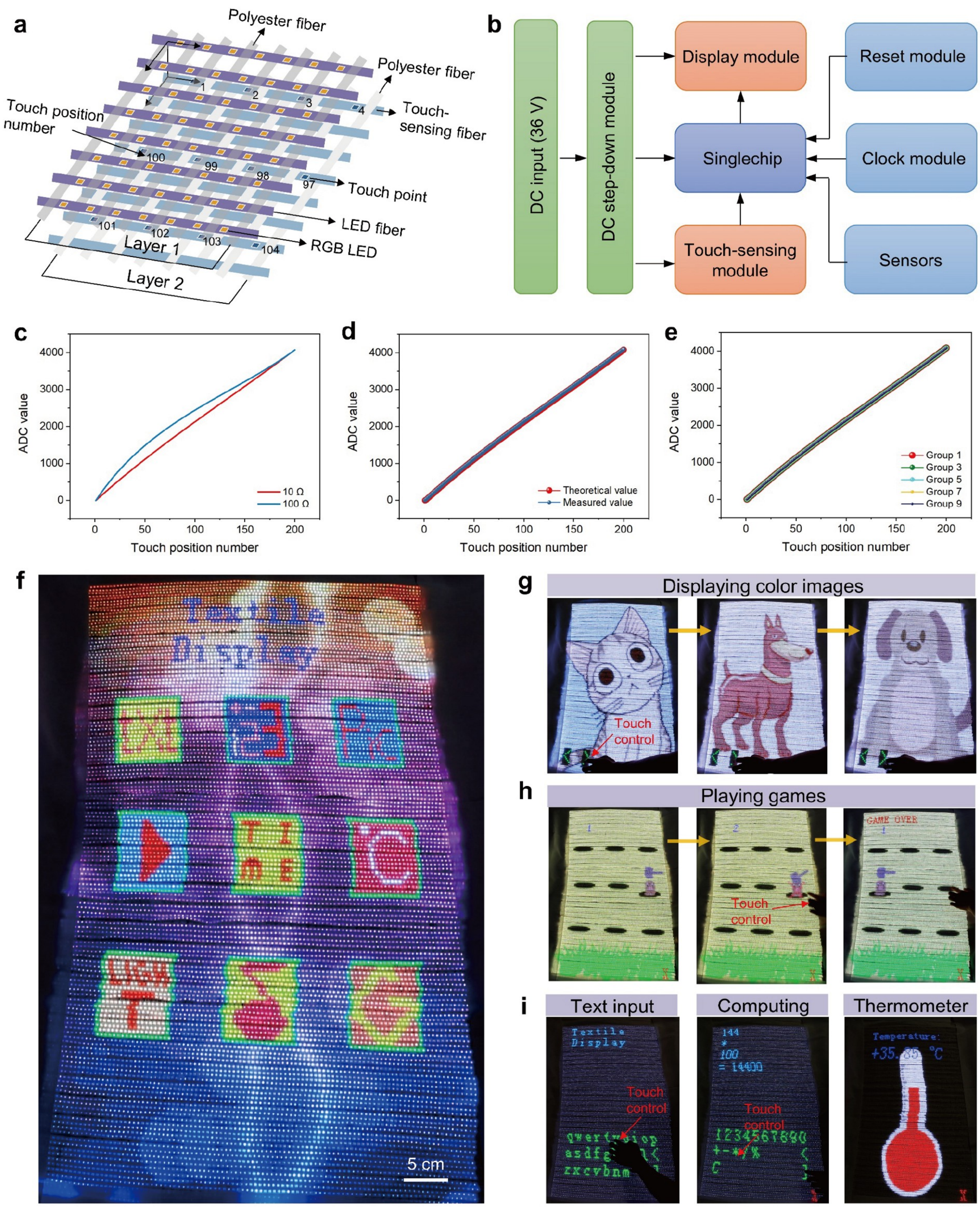

Figure 4 Application demonstrations of integrated electronic textile system. (a) Schematic diagram of integration design of RGB LED fibers and touch-sensing fibers. (b) Flow chart of module design of integrated electronic textile system. (c) The relationship between the returned ADC values and numbers of touch position with different values of *R*. (d) The returned ADC values at different touch positions. (e) Consistency of returned ADC values for the 9 groups of touch-sensing fibers. (f) Photograph of the integrated electronic textile system displaying color images of Apps. (g) Photograph of the color images being switched through touch control. (h) Photograph of the textile system displaying a "whack a mole" game. (i) Photograph of the textile system displaying hand text input, computing and thermometer applications.

where A is the returned ADC value, N is the gauge of the ADC module (4095 in this study), n is the total number (200) of the imparted resistances, k is the number of the touched point, R is the value of the imparted resistance, and R_0 is the value of the resistance to avoid the random value.

Thus, the value R was modified to ensure the linear relationship between the position and the ADC value. The value of R should be much higher than the resistance of the printed circuit to distinguish the touch position. For example, when the R was 100 Ω, the relationship between ADC value and touch position number was not linearly related, because the value of R_0 was not much higher than R (Fig. 4c). Thus, the value of R was selected as 10 Ω, and the returned ADC value well agreed with the theoretical value (Fig. 4d). For precise touch recognition, the touch-sensing fibers consisted of 200 touch points were used to control 1600 RGB LEDs, that was, each touch point controlled 8 (2 × 4) RGB LEDs. The ADC values returned by touch-sensing fibers consisted of 9 groups showed a high consistency (Fig. 4e), thus the touch point could be precisely identified in the textile system (Fig. 4b).

The integrated textile system was highly flexible and stable for practical applications. For instance, the textile system could normally work as it was folded together (Video S2). The performances of display and touch-sensing module were well maintained after 5000 cycles of bending deformations (Figs S17, S18). Moreover, the temperature of the textile system was less than 25°C even after continuously working for 10 h at a displaying luminance of 1000 lx (Fig. S19), indicating its promising prospect in wearable applications.

By integration of touch-sensing module, the electronic textile system was demonstrated to realize various human-machine interaction functions like smart phones and computers, such as displaying color images, hand input of text, hand painting, computing, time keeping, thermometer, and playing music and games (Fig. 4f, Video S3). Specifically, these electronic functions were achieved by three steps: a) the touch-sensing fibers in the whole textile system received the various orders from users; b) the data from the touch-sensing fibers were sent to singlechip; c) the singlechip processed the data and feed backed to the corresponding LEDs in the woven LED fibers for display dynamic images. Users could choose different Apps by touching the corresponding images. For instance, full-color images could be switched through a touch control on the textile (Fig. 4g, Video S4). In addition, a "whack a mole" game which needed close interaction between displaying and touch-sensing modules was realized (Fig. 4h). In this game, a mole would randomly appear in one of the holes displayed in the integrated electronic textile system. The user should touch the correct area in the textile to whack the mole, and the number of the caught mole was calculated. Once the user touched the vacant hole, the game would be over by displaying a text of "GAME OVER", and the game score could also be demonstrated on the textile (Video S5). Thanks to the precise touch recognition, the text including capital letter, small letter, digit and punctuation could be input by hand (Fig. 4i). Moreover, the typing function could be realized to satisfy the requirement of precise and complex computing applications (Videos S6, S7). Such electronic textile could also achieve other functions by integrating with various sensors such as thermometers and illuminometers (Fig. 4i, Videos S8, S9). The timer application could be realized by integrating with a clock module (Video S10), which could be controlled by touching "start", "pause" and "reset" bottoms to record time consumption. With the integration of loudspeaker in the singlechip microcomputer, the textile could also play music. It could be stopped and skipped at any time, and the volume could be tuned through the corresponding bottoms (Video S11). In the future, more interaction applications could be achieved by integrating other electronic modules in the textile system.

CONCLUSIONS

In conclusion, we present a large-area touch-control electronic textile system (144 × 100 × RGB LEDs) that can display full-color images and videos by weaving LED fibers and touch-sensing fibers. The difficulties of continuously displaying full-color frame images which the previous display textile did not overcome were effectively addressed by designing step-voltage-drop mode and parallelly transmitting circuits. Our electronic textile system showed high luminance, long lifespan, full color and low driving voltage, which could serve as new-generation information interaction interfaces to effectively bridge the gap between people and electronic devices.

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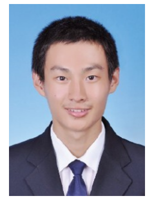
Author contributions Peng H conceived the idea; Zou J and Feng G designed the experiments; Zou J wrote the original draft. Chen P and Zou J participated in the design and layout of the pictures and reviewed the manuscript; Peng H and Chen P supervised the work and reviewed and revised the manuscript. All authors contributed to the general discussion.

Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Supplementary materials are available in the online version of the paper.



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可显示全彩图片和视频的集成电子织物系统

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摘要 具有显示等功能的智能电子织物有望为可穿戴设备带来传统刚性器件所无法实现的变革性发展机遇. 赋予织物以显示功能的一个经典方法, 是将发光纤维编织成织物, 并通过设计驱动电路而实现显示. 然而, 目前电子织物面临的一个重要挑战是难以显示全色彩图片和视频. 为此, 我们通过将LED发光纤维、触摸感应纤维和涤纶纤维进行编织, 制备得到了大面积的集成电子织物系统(尺寸为72 cm × 50 cm). 通过设计低压供电模式和数据并行传输电路, 该织物系统可实现全色彩图片(色域达117.6% NTSC)和视频(刷新率为11.7 Hz)显示. 通过集成触摸感应纤维, 该织物系统可实现像智能手机和电脑一样的触控交互功能, 如手写输入文本、绘画、计算器和游戏. 面向可穿戴应用需求, 该织物系统具有良好的稳定性和耐久性, 可经受5000次弯曲变形测试. 该集成电子织物系统还具有与传统织物相近的柔性和透气性, 有望作为一种新型人机交互界面, 改变人们与电子器件的交互方式.

