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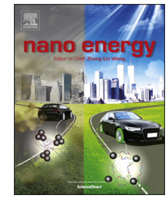

Communication

Self-powered wireless optical transmission of mechanical agitation signals

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ABSTRACT

The ubiquitous sensors have accelerated the realization of Internet of Things (IoT) but also raised challenges to the current overcrowding radio frequency (RF) based communications. The optical wireless communication (OWC) that utilizes the wide optic bandwidth can well solve the spectrum crisis and is an appealing complementary solution to the IoT applications. However, the additional direct current (DC) power supply and complicated modulating and power management circuits may limit the large-scale deployment of OWC systems. In this paper, by integrating with triboelectric nanogenerators (TENGs), the light-emitting diode (LED) could be directly transformed into a wireless transmitter that conveys the information associated with mechanical stimuli without additional power supply. With the customized TENG devices and the help of advanced image processing and machine learning techniques, three demonstrations with functions of optical remote control, pressure sensing, and security authentication, were demonstrated. The concept and results in this paper may greatly broaden the application of IoT through the integration of OWC and TENG.

1. Introduction

With the popularity of Internet of Things (IoT), the ubiquitous existence of sensors has brought great convenience to daily life, but it also raised serious challenges to the wireless communication access [1–3]. Current solutions for IoT communications are dominated by traditional radio frequency (RF) based techniques, e.g., the wireless local area networks (WLAN), Cellular, Bluetooth, Zigbee, and Radio-frequency identification (RFID) and etc. [4–8]. However, the RF band of the electromagnetic spectrum is fundamentally limited in capacity and costly since most sub-bands are exclusively licensed, resulting in spectrum crisis especially in the scenarios with dense sensors [9,10]. In this context, the optical wireless communications (OWC) which utilizes the huge and unlicensed optic bandwidth for data transmission, provides a promising alternative to alleviate the spectrum crisis [11–13]. Besides, the OWC technology has many other attractive features such as worldwide availability, radiation-free, and high-capacity, and thus is regarded as an appealing complementary communication solution for IoT applications [14].

According to the different optical carriers used by transmitters, OWC can be categorized into three main types, i.e., visible, infrared (IR) and ultraviolet (UV) light communications [15–17]. The OWC can also be classified based on the receiver types, including the photo detector and camera based methods [18,19]. Nevertheless, existing OWC transmitters usually rely on direct current (DC) power supply, which induces high maintenance cost and limits its applications where only the event trigger is needed to monitor. To the best knowledge of the authors, there is no appealing scheme to address this problem. The triboelectric nanogenerator (TENG) first invented by Wang et al. in 2012, is an emerging mechanical energy harvesting technology as well as the mechanosensing technique that originates from the displacement current in the Maxwell's equations and can easily produce high-voltage up to thousands of volts [20–26]. Such characteristics make it ideal for powering the light-emitting diodes (LEDs) that have a threshold for operation voltage but require only a small amount of current. For example, a small TENG device (size of 1 in. × 1 in.) can easily light up tens of LEDs with a simple contact and separate operation [27]. Therefore, the TENG may be employed as a competitive power supply

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for OWC to wirelessly monitor mechanical stimuli.

In this paper, we demonstrated a self-powered, TENG-driven OWC with the capability of wireless control, sensing and even authentication. The concept of self-powered OWC was firstly proposed, and by an integration with TENG-based sensing devices, a LED array can directly work as a wireless transmitter to convey the information associated with mechanical stimuli without additional electrical power supply. With different TENG devices and machine learning techniques, three systems with functions of remote control/event monitoring, pressure sensing, and security authentication, were then implemented and evaluated for practical feasibility in the laboratory environment. Other possible applications and potential improvements are discussed in this paper as well. The concept and results in this paper may greatly broaden the application of IoT through the integration of OWC and TENG.

2. Results

2.1. Design of the system framework

The systematic concept of the self-powered OWC system driven by TENG is illustrated in Fig. 1. The whole system can be divided into two sections, i.e., the transmitter and the receiver. The transmitter is mainly consisted of the TENG device and the LED or LED array. Under mechanical stimuli, corresponding units of the TENG device would be triggered and produce a high voltage output, which can easily power one to several LEDs without any rectification or analog to digital conversion (ADC) modules. By associating the LEDs with corresponding TENG units, the status information (location, elapsed time, force, and etc.) of the external mechanical stimuli can be reflected by the "on-off" blinking of the corresponding LEDs. In other words, the TENG works as both the event trigger and the power source for the OWC transmitter. Compared to the traditional scheme, the one we proposed does not rely on additional electrical power sources and eliminates the need of complicated power management circuits. In practice, various types of mechanical events or triggers (for example, moving, pressing, vibrating, kicking or sliding) based on TENG can be designed and adopted (add several references on TENG sensors) [28–31]. The LED size, power and type (optical carrier band) can also be optimized according to the requirements of the specific applications.

As for the receiver, either photo detector or camera can be deployed to receive the optical information according to the requirements in specific applications. Here, the camera based detection scheme is adopted for a simple and low-cost implementation. The camera captures the video of the LED array at a configured frame rate (denoted as f_p which is typically 30 frames per second). According to the Nyquist-Sampling theorem, the desired information signal conveyed by the LED blinking can be guaranteed for perfect recovery with appropriate signal processing as long as the desired signal frequency f_i is less than half of the sampling rate, i.e., $f_i < f_p/2$ [32]. The subsequent information detection process in our OWC system includes the region of interest selection (extract the desired image region from the original picture to reduce the processing time of following steps), image calibration (make proper corrections to the image rotation caused by the receiver position), color space transformation (transform the image to other color space and enhance the desired information component), image processing (apply advanced techniques for further processing), and the final information decoding (obtain the desired information).

To better illustrate the concept of the self-powered OWC driven by TENG, we implemented three demonstrations for different applications in this work.

Application 1. Self-powered wireless remote control

In this application, we utilized the self-powered OWC to realize the wireless remote control. A double-electrode contact-separation (CS) mode TENG (size of 1 in. × 1 in.) was fabricated as shown in Fig. 2(a). The CS-TENG uses the copper foil and polytetrafluoroethylene (PTFE) film as the positive and negative triboelectric surfaces, respectively. The operation of the TENG is based on coupling between triboelectrification and electrostatic induction [23]. Initially, the physical contact between two triboelectric layers of different materials creates opposite charges on the two surfaces in contact. Then as triggered by the mechanical force, the relative motion between opposite charges breaks the existing electrostatic balance, which builds a potential difference between the

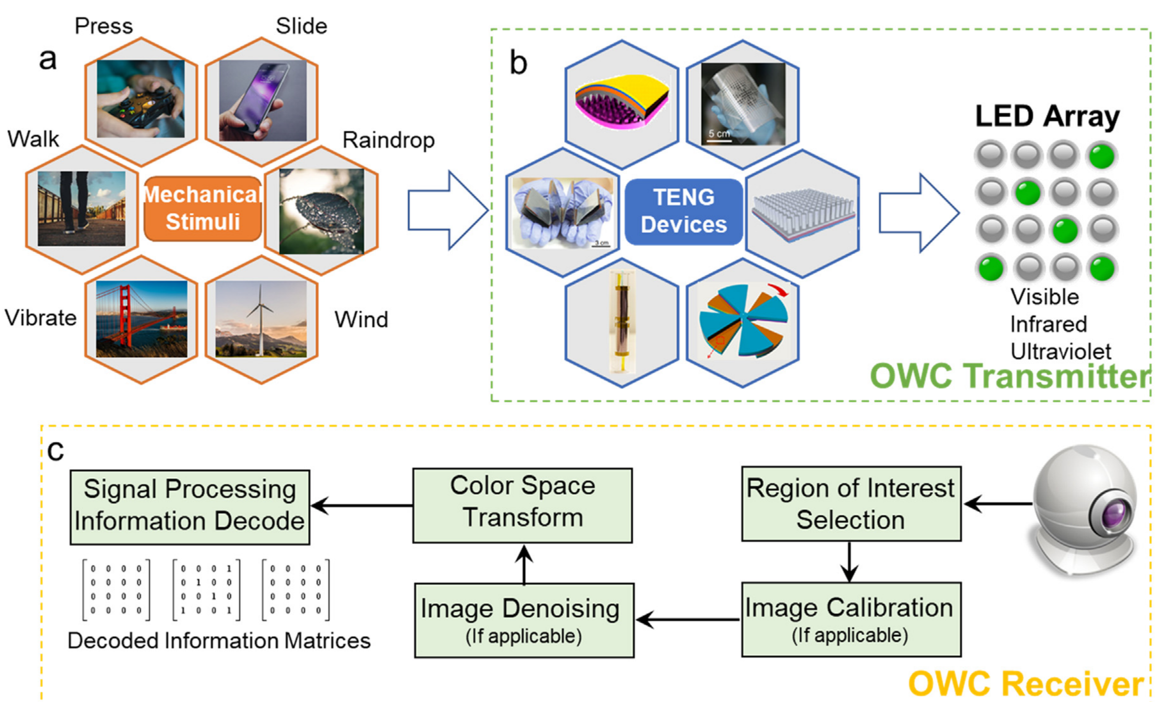

Fig. 1. Schematic illustration of the self-powered OWC driven by TENG. (a) The potential mechanical stimuli that can be monitored. (b) Use different TENG devices to be triggered by the mechanical motions and form the OWC transmitter with the LED array. (c) The OWC receiver to detect the information conveyed by the light.

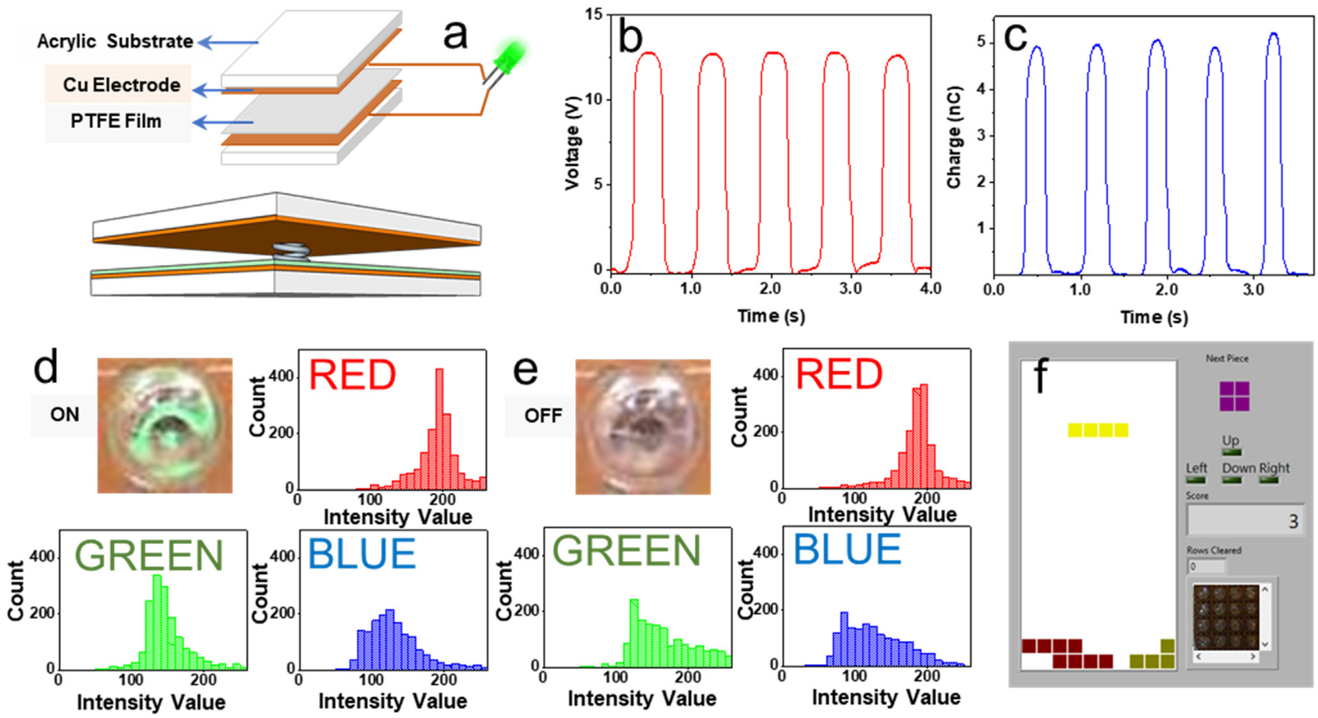

Fig. 2. Self-powered wireless remote control. (a) The schematic diagram showing the TENG device structure and the circuit connection of the TENG device with the LED lamp. (b) The open-circuit voltage output of the TENG device triggered by hand. (c) The transferred charge amount of the TENG device triggered by hand. (d) The intensity histogram of the RGB color space of a typical "on" LED image. (e) The intensity histogram of the RGB color space of a typical "off" LED image. (f) The Tetris game interface played with the proposed system (programmed via Labview 2016).

electrodes and drives free electrons in the electrodes to flow to rebalance the electrostatic field. When the layers move back, the electrons flow back to return to the original equilibrium [23]. In a word, when a "press and release" mechanical force is applied to the TENG device, a pulsed voltage can be delivered, as illustrated in Fig. 2(b). Then by wiring TENG to a LED, such voltage output will drive the LED to have a "on-off" behavior, which can be captured by the video camera (LifeCam Studio, Microsoft) at the receiver. It should be noted here that different modes or structures of TENG can be deployed separately or together, if various kinds of mechanical motions, for example, sliding, vibration and etc., need to be detected.

By analyzing the "on-off" status of the LED from the image captured in each frame, the mechanical motion can be detected and the remote control will be realized. Typical "on" and "off" LED images together with their intensity histogram of the red-green-blue (RGB) color space are shown in Fig. 2(b) and (c). Distinctive difference in the intensity distribution of the "on" and "off" images, especially in the green component intensity, can be observed. Here we propose an adaptive intensity-threshold based algorithm to realize the status judgement. The detailed description of the detection scheme is provided in Supplementary material Note S1. Additionally, we fabricated four such TENG units to form a simplest direction keyboard and successfully played the Tetris game using it, as demonstrated in Fig. 2(f) and Supplementary Movie S1.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nanoen.2018.03.044.

Application 2. Self-powered wireless tactile array for pressure detection

In this application, we utilized the self-powered OWC to realize wireless pressure detection. As a proof-of-concept demonstration, a TENG tactile array (touch panel) with 4 × 4 taxels was fabricated, and its structure is illustrated in Fig. 3(a) left. Each taxel has a square size of 1 cm × 1 cm. The touch panel uses indium tin oxide (ITO) as the electrode, a polydimethylsiloxane (PDMS) film as the triboelectric layer and a PET film as the substrate, which guarantees the transparency and flexibility. As shown in Fig. 3(b), it is transparent and flexible, which is suitable for the electronic trends nowadays. The working mechanism of this tactile array is based on the single-electrode contact-separation mode of TENG [23]. In this case, the pressing object acts as the other triboelectric layer while a reference grounded electrode is taken as the other electrode. The output performance of the fabricated TENG tactile array is provided in Fig. S1(a) and (b), where the finger pressing is used as the mechanical stimulus for testing.

The circuit diagram is shown in Fig. 3(a) right, where each taxel is wired to a corresponding LED. According to the previous study, the output voltage of each touching is proportional to the pressing force to a certain extent [23,29]. Meanwhile, the higher the driving voltage is, the brighter the LED will be. Since the green light LEDs were used in this study, the brighter light would contain stronger green component. On the green component quantification, there is a trap easily to be neglected, which is that a large value in the green channel can guarantee a green-like pixel in the original image, if and only if the values in red and blue channels are smaller [33]. Consequently, in this work, a green component intensity detection algorithm is proposed to extract and quantify the brightness of the LED light, as described in Supplementary material Note S2. Typical LED images and the corresponding green component intensity images after processing at different forces applied to the taxel are provided in Fig. 3(c). The white area in the intensity image is used to indicate the intensity of the green component: the larger, the higher. Additionally, experiments were conducted to quantify the relationship between the green component intensity in the captured LED image and the applied force, which gives a great linearity as in Fig. 3(d). As a tactile array, the system can detect the magnitudes of forces applied to different taxels simultaneously. When four taxels on one diagonal of the tactile array were pressed with four fingers, the detected intensity can clearly reflect the force distribution, as shown in Fig. 3(e).

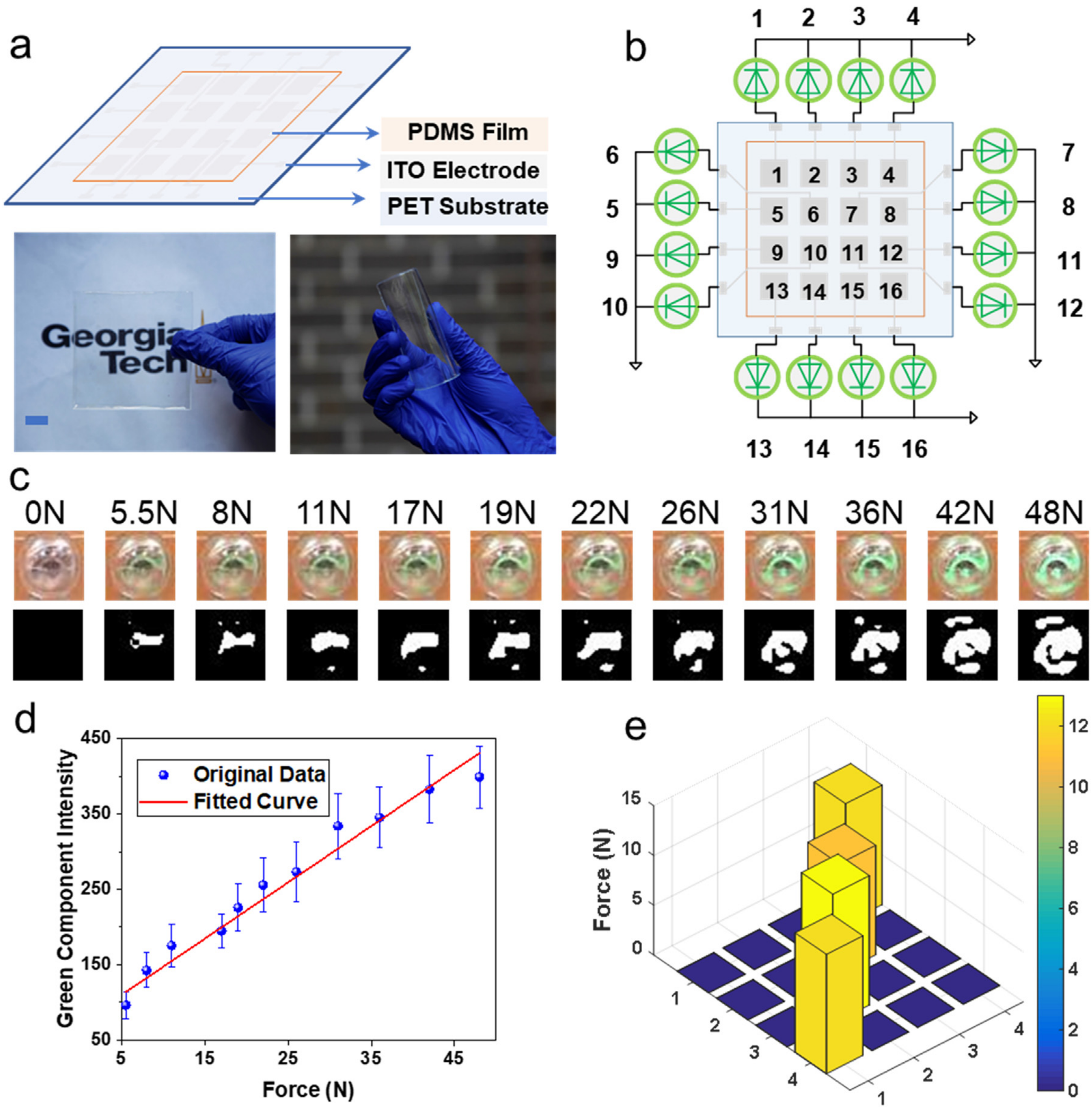

Fig. 3. Self-powered wireless tactile panel for pressure detection. (a) The schematic diagram (up) and photographs (bottom) of the TENG device (a 4 × 4 tactile array), which is transparent (bottom left) and flexible (bottom right). Scale bar: 1 cm. (b) The circuit connection of the TENG device with the LED array (a 4 × 4 LED array). (c) The typical LED images and the corresponding green component intensity images after processing at different forces applied to the tactile pixel. (d) The relationship between the green component intensity detected from the captured LED image and the force applied to the corresponding taxel. The pressing was simulated by a 1 cm × 1 cm acrylic plate covered with nitrile glove and driven by a linear motor. (e) The detected force output based on the relationship obtained in (d) when the four taxels on the diagonal were pressed simultaneously.

Application 3. Self-powered wireless touch panel for user authentication/identification

In this application, we utilized the self-powered OWC to realize user authentication/identification. Specifically, the tactile array fabricated in Application 2 can also be used to sense the sliding motion on it and power the LED array. The voltage generation mechanism here is based on the single-electrode sliding mode of TENG [23], and the output performance is illustrated in Fig. S1(c) and (d), where the finger sliding is adopted as the mechanical stimulus for testing. The users' sliding biometrics, including the touching force and the sliding speed, can be captured by this OWC system. Therefore, the device can work as an intelligent interface for authentication or identification to distinguish the users even with the same sliding password.

In this work, five people were invited repeatedly to slide a z-type password on the touch panel (Fig. 4(a) left) for 50 times each. The LED array were lighted accordingly, as illustrated in Fig. 4(a) right. Figs. 4(b) and S2 show the detected intensity-time plots of different users. Two factors of user biometrics can be extracted from these plots, e.g., the signal magnitudes (denoted as *A*, reflecting the touching force) and the sliding latencies (denoted as *T*, reflecting the sliding speed). For the z-type sliding across the “1–2–3–4–7–10–13–14–15–16” taxels, a total of 19 features can be obtained accordingly, i.e. 10 signal magnitudes and 9 sliding latencies. The radar plot of the normalized mean feature values of five users is shown in Fig. 4(c), which shows the distinctive “slide to unlock” behaviors. To improve the accuracy and robustness of the authentication and identification, we adopted the supervised machine learning to build up the user profiles for classification [31,32]. The working process is illustrated in Fig. 4(d). The detailed description of the proposed algorithm is provided in Supplementary material Note S3 and the working principle of the core method which is called the supporting vector machine (SVM) is introduced in Supplementary material Note S4 [34]. The 50 sets of data from each user were randomly split into two halves, one for training and the other for testing. The classifier performance was optimized by tuning the decision threshold value and comparing the resulting false rejection

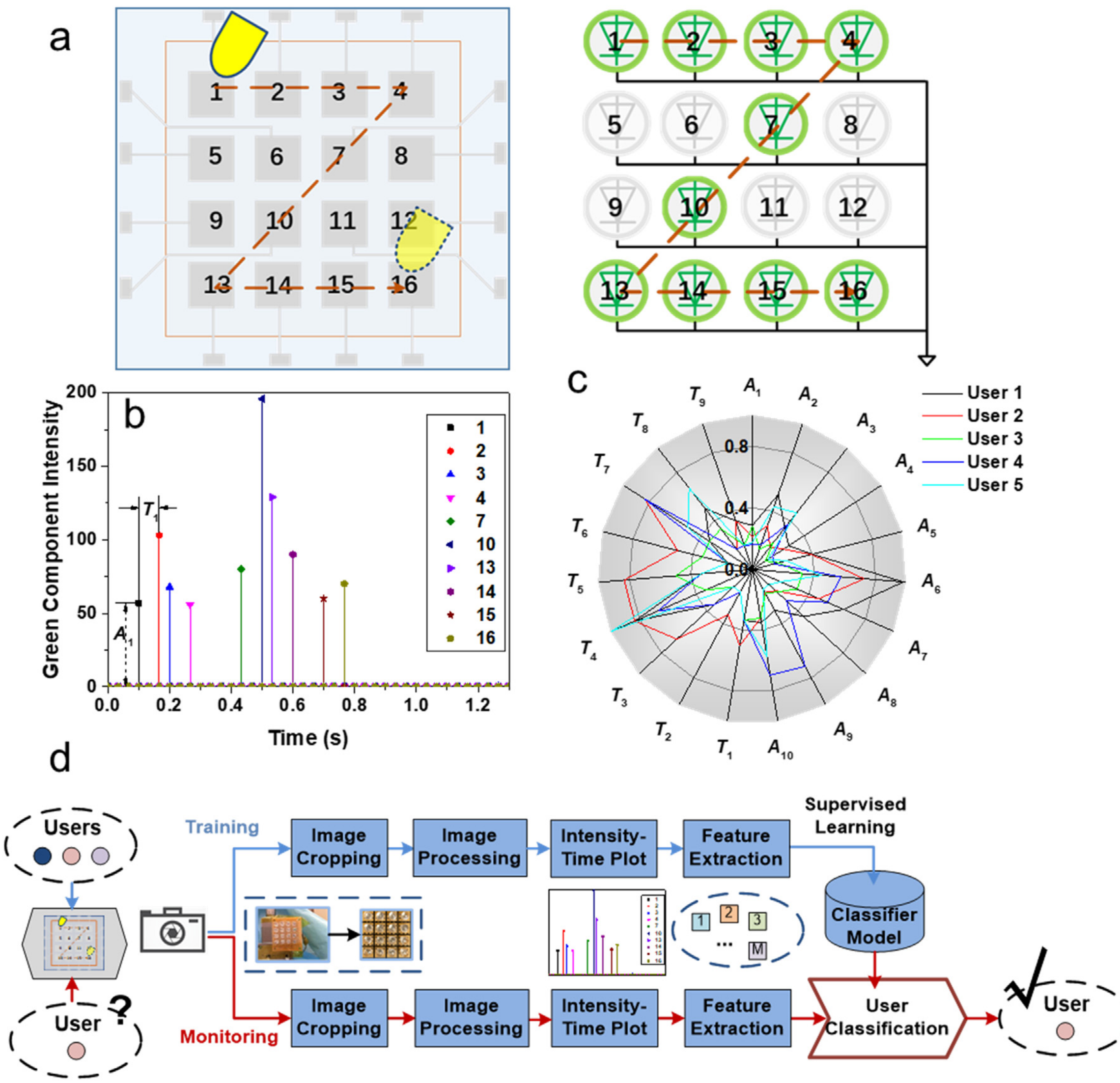

Fig. 4. Self-powered wireless touch panel for user authentication/identification. (a) The schematic diagram of a z-type "slide to unlock" action on the TENG based touch panel (left) and the corresponding response of the connected LED array (right). (b) The intensity-time plot of User 1 and the sliding features defined to construct user profile models. Signal magnitudes (LED intensity or touching force) and sliding latencies are denoted as *A* and *T* respectively. (c) The radar plot of the normalized mean feature values of five users after they repeat the z-type "slide to unlock" action for 50 times each. A total of 19 features, 10 signal magnitudes and 9 sliding latencies, can be extracted from the z-type "slide to unlock" action going through 10 taxels. (d) The process flow of the proposed algorithm for user authentication/identification based on the supervised machine learning scheme.

rate (FRR) and false acceptance rate (FAR) (the full definition of the classification related rates is summarized in Supplementary material Note S5) [35]. With the optimal decision threshold of 0.44, the tradeoff between a low FRR and a low FAR can be well satisfied so that an equal error rate (EER) as low as 0.92 can be achieved (see Fig. S3(a)). A standardized receiver operating characteristic (ROC) curve (Fig. S3(b)), defined as the plot of the true positive rate (TPR) against the FAR at various threshold settings, is calculated and gives an enclosed area of 0.989 (the closer to 1, the better), indicating a very good classifier. In this condition, the classifier has the accuracy of 95.2%.

3. Discussion

In this work, the concept of the self-powered OWC driven by TENG is proposed. By powering the LED array with the TENG sensing device, the TENG can work as both the mechanical event trigger and the power source of the LED, and they can constitute a simplest OWC transmitter with no additional power supply or complicated circuits. With the help of a video camera at the receiver and advanced image processing techniques, the information associated with the mechanical stimuli and conveyed by the LED light can be decoded appropriately. By considering the "on-off" feature, the "intensity" feature and the inherent biometrics feature step by step, three types of demonstrations with the capability of wireless control, pressure sensing and security authentication were implemented and evaluated for practical feasibility in the laboratory environment. For practical use, the specific devices, techniques and parameter configuration can be well designed and optimized according to the corresponding circumstances. Moreover, it can easily achieve multi-target monitoring if more than one such self-powered OWC transmitter is deployed and only one receiver is needed. The concept and results in this paper may greatly broaden the application of IoT through the integration of OWC and TENG.

4. Methods

4.1. Fabrication of the TENG controller unit for Application 1

Acrylic plates of 1 in. × 1 in. were laser cut (PLS6.75, Universal Laser Systems) and used as the substrates for TENG electrodes and triboelectric materials. Each TENG unit consisted of two acrylic plates, with one covered with copper tape only and the other covered with copper tape and then PTFE tape. A spring was used as the spacer and Kapton tape (Model S-7595, 3M) was applied to assemble all the parts.

4.2. Fabrication of the TENG tactile array for Applications 2 and 3

An electrode mask of 6 cm × 6 cm made of PVC film was firstly fabricated using laser cutting (PLS6.75, Universal Laser Systems). Then it was attached to a PET film (6 cm × 6 cm) and ITO electrode was deposited onto polyethylene terephthalate (PET) via sputter coating (PVD75, Kurt J). A PDMS film of the same size with the thickness of 500 μm was made through mold casting, and then attached to the ITO coated PET film.

4.3. Electrical output measurements

The open-circuit voltage and transferred charge from the TENG device were measured by a Keithley 6514 system electrometer. For the intensity-force testing in Fig. 3(c) and (d), the pressing motion was stimulated using a 1 cm × 1 cm acrylic covered by a nitrile glove and driven by a programmable linear motor. All other signals were from human pressing or sliding.

4.4. Signal processing and system implementation

The video capturing was realized with the Microsoft Lifecam Studio webcam. The region of interest selection, image calibration, the graphical user interface and the Tetris game were implemented using LabVIEW 2016 powered with the Vision and Motion toolbox. The signal processing including denoising, color space transformation, green component intensity detection, feature extraction and classification, was implemented with MATLAB® 2016b. Please refer to Supplementary Notes for the details of the proposed algorithm for green component intensity detection and supervised machine learning based classification.

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W. Ding, C. Wu, and Y. Zi contributed equally to this research. W. Ding, Y. Zi and Z. L. Wang conceived the idea. W. Ding designed the software platform for the whole system. C. Wu designed and fabricated the TENG devices. H. Zou helped fabricate the transparent and flexible electrodes. C. Wu, J. Wang, A. Wang and J. Cheng conducted the experiments and demos. W. Ding, Y. Zi, C. Wu and Z. L. Wang analyzed the data and prepared the manuscript.

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Competing financial interests

The authors declare no competing financial interests.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2018.03.044.

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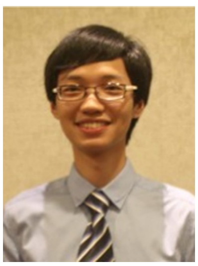

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