SHORT COMMUNICATION

Building self-powered emergency electronics based on hybrid nanogenerators for field survival/rescue

Xiaojing Cui¹ | Shengli Cao¹ | Rui Guo¹ | Saeed Ahmed Khan² | Gang Xie³,⁴ | Zhigang Tian⁵ | Shengbo Sang¹ | Hulin Zhang¹,⁶

¹Micro Nano System Research Center, Key Lab of Advanced Transducers and Intelligent Control System of the Ministry of Education & College of Information and Computer, Taiyuan University of Technology, Taiyuan, China
²Department of Electrical Engineering, Sukkur IBA University, Sukkur, Pakistan
³Shanxi Key Laboratory of Advanced Control and Intelligent Information System & School of Electronic and Information Engineering, Taiyuan University of Science and Technology, Taiyuan, China
⁴College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan, China
⁵Industrial Technology Development Research Center of Shanxi Province, Taiyuan, China
⁶State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu, China

Abstract

Harvesting energy from human body in multiple ways is pivotal for achieving powering emergency electronics effectively. Herein, we report a hybrid nanogenerator that is based on the coupling of a triboelectric nanogenerator (TENG) and electromagnetic generator (EMG). By utilizing a copper coil in multiroles, the energy grabbing units can operate independently without interfering, revealing a superior performance in scavenging biomechanical energy from human motions. The hybrid device by encapsulation exhibits an excellent environmental stability. When wearing the fabricated device, the TENG and EMG can generate the output voltage about 4 and 1.5 V, respectively, which can be directly stored into a capacitor. By integrating with a battery, the established self-powered device can actively provide a geographic coordinate in real time in the wild where there is no power supply or network connectivity. Our work paves a way for the further exploration based on hybrid nanogenerators in self-powered wearable/portable emergency electronics that can be applied in exploration, travel, work, as well as rescue in the wild without power apply and Internet.

KEYWORDS

biomechanical energy, hybrid nanogenerator, localizer, self-powered, triboelectric nanogenerator
1 | INTRODUCTION

Mechanical energy, as one of the most common ambient energies, is available almost anytime and anywhere in our living environment, such as vibration, ambient sound, and biomechanical energy. In recent years, a lot of effort and attention has been paid to mechanical energy-harvesting technologies. These technologies can be divided into three types according to working principles, including piezoelectric nanogenerators (PENGs) based on piezoelectricity, electromagnetic generators (EMGs) based on electromagnetic induction, and triboelectric nanogenerators (TENGs) based on the coupling of triboelectrification and electrostatic induction. However, PENGs, with relatively lower output, are fabricated by using piezoelectric materials which are synthesized through a series of complex procedures, making the device construction low cost-effective. In addition, the EMG is subject to its size, resulting in a quite low output voltage with a relatively high current when the device size is limited, while the TENG is characterized of a high voltage but low current compared to the EMG. Accordingly, the hybridization of multiple energy-harvesting techniques is a necessary and promising approach to achieving harvesting mechanical energy efficiently. Although some hybrid energy devices have been invented, the accessibility and practicability still need to be improved.

Emergency electronics are of significance for field survival or rescue where the steady energy supply is not available, which has raised urgent and challenging requirements in sustainable and environmentally adaptable power supply. However, the existing emergency electronic productions mostly work by extracting power from built-in batteries/capacitors or external power sources. In practice, these energy storage units are usually not reliable and stable in the wild where the climate is harsh and capricious. Therefore, in future field emergency survival/rescue, it is highly desirable to develop self-powered technologies by converting ambient energy into electricity that can actively drive functional electronics without using any external power sources.

To achieve the goal of transforming environmental energy into sustaining electricity for driving small electronics, we introduce a new hybrid nanogenerator by the coupling of an EMG with a TENG. The energy-harvesting units of our hybrid device can operate independently without interfering as well as produce excellent output signals. By integrating with existed commercial electronics, a hybrid nanogenerator-based self-powered localizer is constructed, which can actively provide a real-time geographic coordinate in the wild without using external power sources or Internet. The concept and design presented in this work can be further applied in various other circumstances for either biomechanical energy-harvesting or field self-powered sensing. Therefore, it is a step further in the development toward nanogenerator-based self-powered electronics.

2 | EXPERIMENTAL SECTION

A magnet (5 mm in thickness and 19 mm in radius) with a polytetrafluoroethylene (PTFE) film (50 μm in thickness) attached was fixed at the top of a plastic axle. A copper coil (wire diameter of 0.5 mm and number of turns of 3000) has the same bottom area with the magnet, which is supported by a steel spring with all of them threaded on the shaft, while the hybrid device with another configuration was fabricated by switching places between the magnet and coil. The enclosed energy-harvesting device is established by placing the hybrid nanogenerator in an acrylic tube with two ends sealed. In our electrical measurement, a low-noise voltage preamplifier (Keithley 6514 System Electrometer) and current preamplifier (Stanford Research SR560), connected with a high-speed data acquisition card, were used to record the output voltage and current of devices, respectively.

3 | RESULTS AND DISCUSSION

The structural design of the hybridized triboelectric and electromagnetic nanogenerator is schematically illustrated in Figure 1A, where the TENG is composed of a PTFE film tightly attached on a magnet and a spring-supported insulation layer-coated Cu coil that not only serves as the single electrode in the TENG but also works as the electromagnetic induction coil in the EMG. A real graph of this device is shed light in Figure S1A. When the device is applied with a vibration, the coil coated with an insulation layer and PTFE film will obtain a periodical contact and separation, forming a typical single-electrode TENG. Here, the coil should be
considered as a metal electrode. The magnet is fixed at the top of the middle axle, as sketched in Figure 1A. The Cu coil can vibrate periodically when the device is subjected to ambient mechanical stimulations. During vibrating, the magnetic flux through the coil will change periodically, leading to an AC current in the external circuit due to electromagnetic induction. Obviously, we can extract the electricity produced by the EMG from the two ends of the coil, as illustrated in Figure S2. Figure 1B shows an AFM image of the PTFE surface. The rough morphology indicates the higher surface charge density on the PTFE film, which can markedly improve the output performance of the TENG.43-45

The basic working mechanism of the hybrid device can be discussed from two individuals, the TENG and EMG. The electricity generation principle of the TENG is based on the coupling of triboelectrification and electrostatic induction. Figure 2A presents an operating cycle of the TENG. At the original position, the PTFE film surface is in full contact with the insulation layer coated on the Cu coil, resulting in equal but opposite triboelectric charges generated on the contact area due to their different triboelectric polarities (i). The triboelectric charges on the PTFE surface and insulation layer can remain for hours or even days because of insulating property.46-48 The produced charges are fully balanced/screened, leading to no electron flow in the external circuit. Once the coil is separated from PTFE, these triboelectric charges cannot be compensated. The positive charges on the insulation layer can induce negative charges on the copper coil electrode, driving electrons to flow from ground to the coil (ii). This process will last and can give an output current signal. When positive triboelectric charges on the insulation layer are fully screened from the induced negative charges on the coil electrode by increasing the separation distance between the coil and PTFE, no output signals can be observed (iii). Subsequently, the coil is reverted to approach the PTFE, the induced negative charges in the coil decrease and the electrons will flow back to ground with a reversed current observed (iv) until the PTFE and insulation layer on the coil and fully contact each other again. This is a full cycle of the electricity generation process for the TENG. The following simulation of electric potential distribution on the TENG is depicted via COMSOL in Figure 2B. The potential difference at the interface enhances significantly as the separation distance increases, which is consistent with the above analysis. Figure 2C demonstrates an entire electricity-generating cycle of the EMG. The calculation of the magnetic field is carried out via COMSOL. From stage i to stage ii, as the space between the magnet and coil is shortened, the magnetic flux through the coil increases, leading to a current through the external circuit. At stage iii, the flux reaches maximum with no output current. Then, the flux decreases from stage iii to stage iv, inducting a reversed current. When the flux no longer decreased and return to the initial state, there will be no current. Therefore, as long as the hybrid device consisted of the TENG and EMG vibrates ceaselessly, periodic contact/ separation and flux variation will be produced, causing the continuous AC output signals. Indeed, the two generators have entirely different electric-generating mechanisms, as well as the coil not only plays a role as a single electrode in the TENG but also serves as a magnetic flux harvester in the EMG, resulting in only one electricity can be extracted from the hybrid device at one time although both the two generators can work simultaneously. Therefore, even though the two generators have a huge difference in output voltage/current and internal resistance, they still can operate independently without interfering.

To evaluate the output performance of the hybrid device, the electrical outputs of TENG and EMG at different vibration frequencies were investigated. As illustrated in Figure 3A,B, the TENG generates an open-circuit voltage of about 4.5 V and a short-circuit current of near 0.02 μA at 11 Hz, respectively. Figure 3C indicates that the output voltage rises up with the increasing loading resistance, while the output power increases with the resistance below 100 MΩ but then decreases. The maximum output power reaches about 0.11 μW at a resistance of 100 MΩ, implying the internal resistance of the TENG nearly equal with 100 MΩ. Figure 3D demonstrates the relationship between the output voltage and frequency, where the voltage can achieve its peak value about 4 V at the resonant mode of 11 Hz. The preferable output can be achieved at the lower resonance frequency, which usually means the feasibility of harvesting biomechanical energy from human motions. By contrast, Figure 3E,F presents, respectively, open-circuit voltage and short-circuit current of the EMG at the frequency of 11 Hz, with the insets expressing the relation between outputs and loading resistance as well as vibration frequency. It is observed that the voltage is about 0.8 V with the current close to 0.5 mA. When the loading resister is of 400 Ω that is approximate to the internal resistance of the EMG, the maximal power can reach 2 mW. Similarly, at the resonance state, a superior output voltage is obtained due to the maximal magnetic flux.
variation at 11 Hz around. The huge internal resistance difference between the TENG and EMG means impossible for direct power matching. Nevertheless, the TENG and EMG can operate simultaneously and the desirable output performance can be achieved from the individual TENG or EMG, which can meet different power requirements. The long-time stability of the hybrid NG was studied here. Both the TENG and EMG were kept running for 30 minutes. As illuminated in Figure S3A,B, the output voltages of the device remain stable during the measuring period. Due to the heat dissipation limitation of the employed vibrator, the continuous working only can last for 30 minutes. Nevertheless, the robustness of
our designed hybrid devices is desirable owing to the lower abrasion, resulting in an excellent long-time stability.

Another configuration of the hybrid device is schematically inserted in Figure 4A. The copper coil is fixed on the top with the magnet supported by a spring. As described in Figure 4A,B, the output voltage and current of TENG are up to 3.5 V and 0.02 μA at 11 Hz, respectively. Similar to that of the first construction, the voltage has a variation trend of the first increase and subsequent drop and can achieve the maximum value at 11 Hz. Correspondingly, the voltage and current of EMG at 11 Hz, about 0.8 V and 0.37 mA, are presented in Figure 4C,D, respectively. With respect to the second hybrid device, the excellent stability is clearly seen from Figure S3C,D, without obvious output decay. The results show that both hybrid devices can deliver a stable output during the uninterrupted operating for 30 minutes. The hybrid devices with two different configurations (the real photograph shown in Figure S1B) have almost the same output performance, which implies the superior structural adaptability and variability of our designed devices.

Although both the hybrid devices show desirable output performances, the second generator possesses a higher convenience and robustness for harvesting biomechanical energy from human walking. This is because the Cu coil was fixed at the top of a plastic axle. No matter whether we will extract energy from the TENG or EMG unit, we just need to connect one or two ends of the fixed coil, which can greatly facilitate and simplify a cable connection.

In practice, the output of TENG or EMG is very susceptible to environmental factors, especially for humidity. Herein, it is necessary to encapsulate the hybrid nanogenerator. As shown in the left bottom of Figure 5A, the energy cell was sealed in a container. Figure 5A,B presents the output voltages of the encapsulated TENG and EMG attained under different ambient humidity, respectively. It can be seen from the right bottom insets of Figure 5 that the output fluctuation is negligible under the ambient humidity ranging from 20% to 90%. Besides, the outputs of the device were studied at different slant angles to the horizon. When the hybrid device is perpendicular to the horizontal plane, the optimal value is acquired, as expressed in Figures 5C and S4. Apparently, the vertical device can deliver the maximal separation and magnetic flux variation by avoiding the horizontal component of gravity and friction between the axle and magnet that can dramatically suppress the resonance of the hybrid device. To verify the capacity of grabbing biomechanical energy from human movements, Figure 5D illuminates the output signals of the
FIGURE 4  A, B, The triboelectric nanogenerator’s (TENG’s) output voltage and current of the hybrid nanogenerator with another configuration with the insets of the schematic diagram and dependence of the voltage on the frequency. C, D, The output voltage and current of the corresponding electromagnetic generator (EMG).

FIGURE 5  A, B, The output voltages of the encapsulated triboelectric nanogenerator (TENG) and electromagnetic generator (EMG) under different humidity, inset of the diagram of the enclosed device, and the relationship between the voltage and relative humidity. C, The voltage of the TENG at different slant angles to the horizon. D, The output voltage of the hybrid nanogenerator worn on human body when walking, inset of charging curves of the 1 μF, 2.2 μF, and 1 mF capacitor. E, An “SOS” LED board lighted up by the TENG. F, The operating self-powered localizer based on the hybrid device working by grabbing biomechanical energy from human motions, a charging curve, and real photograph of the device.
hybrid device when a person is walking around with the device being held in hand vertically. The TENG and EMG generate the output voltage about 4 and 1.5 V, respectively, which can be directly stored into a capacitor. As depicted in the insets of Figure 5D, the output of the TENG can be utilized to charge a 1 and 2.2 μF capacitor, respectively, while a 1 mF capacitor can be charged to 4 V with 20 seconds by the EMG. The sustainable power output is of significance in the wild where the steady energy supply becomes difficult. Figure 5E illustrates a “SOS” display board, composed of two groups of LEDs with opposite polarities, lighted up by the TENG when shaking, which might be used as an SOS in emergency. Furthermore, a 10 mAh lithium ion battery can be charged closely to 3 V within 120 seconds by the EMG, as depicted in Figures 5F and S5. The insets of Figure 5F demonstrate the stored electricity can easily power a GPS localizer, realizing a self-powered locator that can display the real-time geographic coordinate in the outdoors without using batteries. Although the SOS display board and GPS localizer are just two examples in typical emergency devices for field survival/rescue, more self-powered emergency devices can be demonstrated based on our hybrid nanogenerator. The results indicate that the hybrid generator has a huge potential in serving as a self-powered emergency devices in the outdoor sports or field exploration where there is no power supply or network connectivity.

4 | CONCLUSION

In summary, we have developed a newly designed hybrid nanogenerator that is subtly integrated of a TENG and EMG. The copper coil plays multiple roles which gives rise to that the TENG and EMG can operate independently. The preferable anti-interference capacity to environment influence is acquired by structural variation and encapsulation, indicating that our device can be used in various harsh circumstances for biomechanical energy harvesting. In addition, a self-powered localizer based on the hybrid nanogenerator was invented to locate in real time, which works by the electricity converted from human motions. Our constructed hybrid device can be used as a supplementary power source in the outdoors. The self-powered locating device not only can offer convenience to the tourists, explorers, and workers in remote areas without network and electricity but also has a potential application in large-scale wireless sensor network construction.

ACKNOWLEDGMENTS

This work is supported by the Scientific and Technological Projects for Distinguished Young Scholars of Sichuan Province (No. 2017JQ0016), Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi (STIP) (No. 201802028), Youth Top Talent Program of Shanxi Province (2018), Shanxi International Cooperation Project (No. 201803D421039), and Key Research and Development Plan of Shanxi Province (No. 201703D111027).

ORCID

Hulin Zhang http://orcid.org/0000-0003-4899-1491

REFERENCES

1. Niu S, Wang X, Yi F, Sheng Y, Zhou YS, Wang ZL. A universal self-charging system driven by random biomechanical energy for sustainable operation of mobile electronics. Nat. Commun. 2015;6:6975.
2. Chen J, Huang Y, Zhang N, et al. Micro-cable structured textile for simultaneously harvesting solar and mechanical energy. Nat. Energy. 2016;1:16138.
3. Chen J, Wang ZL. Reviving vibration energy harvesting and self-powered sensing by a triboelectric nanogenerator. Joule. 2017;1:480-521.
4. Lin Z, Yang J, Li X, et al. Large-scale and washable smart textile based on triboelectric nanogenerator arrays for self-powered sleeping monitoring. Adv. Funct. Mater. 2018;28:1704112.
5. Zhang H, Yang Y, Su Y, et al. Triboelectric nanogenerator for harvesting vibration energy in full space and as self-powered acceleration sensor. Adv. Funct. Mater. 2014;24:1401-1407.
6. Cui X, Zhang H, Cao S, Yuan Z, Ding J, Sang S. Tube-based triboelectric nanogenerator for self-powered detecting blockage and monitoring air pressure. Nano Energy. 2018;52:71-77.
7. Chen J, Yang J, Li Z, et al. Networks of triboelectric nanogenerators for harvesting water wave energy: a potential approach toward blue energy. ACS Nano. 2015;9:3324-3331.
8. Wang ZL, Song JH. Piezoelectric nanogenerators based on Zinc Oxide nanowire arrays. Science. 2006;312:242-246.
9. Arico AS, Bruce P, Serosati B, Tarascon JM, van Schalkwijk W. Nanostructured materials for advanced energy conversion and storage devices. Nat. Mater. 2005;4:366-377.
10. Huynh WU, Dittmer BJ, Alvisatos AP. Hybrid nanorod-polymer solar cells. Science. 2002;295:2425-2427.
11. Dresselhaus MS, Chen G, Tang MY, et al. New directions for low-dimensional thermoelectric materials. Adv. Mater. 2007;19:1043-1053.
12. Zhang N, Tao C, Fan X, Chen J. Progress in triboelectric nanogenerators as self-powered smart sensors. J. Mater. Res. 2017;32:1628-1646.
13. Chen J, Zhu G, Yang J, et al. Personalized keystroke dynamics for self-powered human-machine interfacing. ACS Nano. 2015;9:105-116.
14. Meng K, Chen J, Li X, et al. Flexible weaving constructed self-powered pressure sensor enabling continuous diagnosis of cardiovascular disease and measurement of cuffless blood pressure. Adv. Funct. Mater. 2018;29:1806388.
15. Zhu G, Chen J, Zhang T, Jing Q, Wang ZL. Radial-arrayed rotary electrification for high performance triboelectric generator. Nat. Commun. 2014;5:3426.
16. Jung W-S, Lee M-J, Kang M-G, et al. Powerful curved piezoelectric generator for wearable applications. Nano Energy. 2015;13:174-181.
17. Chun JS, Kang N-R, Kim J-Y, et al. Highly anisotropic power generation in piezoelectric hemispheres composed stretchable composite film for self-powered motion sensor. *Nano Energy*. 2015;11:1-10.

18. Shenck NS, Paradiso JA. Energy scavenging with shoe-mounted piezoelectrics. *IEEE Micro*. 2001;21:30-42.

19. Shin S-H, Kim Y-H, Lee MH, Jung J-Y, Nah J. Hemispherically aggregated BaTiO_3 nanoparticle composite thin film for high-performance flexible piezoelectric nanogenerator. *ACS Nano*. 2014;8:2766-2773.

20. Cha SN, Seo J-S, Kim SM, et al. Sound-driven piezoelectric nanowire-based nanogenerators. *Adv. Mater*. 2010;22:4726-4730.

21. Jin L, Ma S, Deng W, et al. Polarization-free high-crystallization β-PVDF piezoelectric nanogenerator toward self-powered 3D acceleration sensor. *Nano Energy*. 2018;50:632-638.

22. Deng W, Yang T, Jin L, et al. Cowpea-structured PVDF/ZnO nanofibers based flexible self-powered piezoelectric bending motion sensor towards remote control of gestures. *Nano Energy*. 2019;55:516-525.

23. Tian G, Deng W, Gao Y, et al. Rich lamellar crystal baklava-structured PZT/PVDF piezoelectric sensor toward individual table tennis training. *Nano Energy*. 2019;59:574-581.

24. Rome LC, Flynn L, Goldman EM, Yoo TD. Generating electricity while walking with loads. *Science*. 2005;309:1725-1728.

25. Donelan JM, Li Q, Naing V, Hoffer JA, Wener DJ, Kuo AD. Biomechanical energy harvesting: generating electricity during walking with minimal user effort. *Science*. 2008;319:807-810.

26. Fan FR, Tian Z-Q, Wang ZL. Flexible triboelectric generator. *Nano Energy*. 2012;1:328-334.

27. Meng B, Tang W, Too Z-H, et al. A transparent single-friction-sur- face triboelectric generator and self-powered touch sensor. *Energy Environ. Sci*. 2013;6:3235-3240.

28. Guo H, He X, Zhong J, et al. A nanogenerator for harvesting airflow energy and light energy. *J. Mater. Chem. A*. 2014;2:2079-2087.

29. Hou T-C, Yang Y, Zhang H, Chen L-J, Wang ZL. Triboelectric nanogenerator built inside shoe insole for harvesting walking energy. *Nano Energy*. 2013;2:856-862.

30. Yang J, Chen J, Liu Y, Yang W, Su Y, Wang ZL. Triboelectric-based organic film nanogenerator for acoustic energy harvesting and self-powered active acoustic sensing. *ACS Nano*. 2014;8:2649-2657.

31. Wang ZL, Lin L, Chen J, Niu S, Zi Y. *Triboelectric Nanogenerator*. Heidelberg, Germany: Springer; 2016.

32. Hu Y, Yang J, Niu S, Wu W, Wang ZL. Hybridizing triboelectrification and electromagnetic induction effects for high-efficient mechanical energy harvesting. *ACS Nano*. 2014;8:7442-7450.

33. Han M, Zhang XS, Sun X, Meng B, Liu W, Zhang H. Magnetic-assisted triboelectric nanogenerators as self-powered visualized omnidirectional tilt sensing system. *Sci. Rep*. 2014;4:4811.

34. Zhang C, Tang W, Han C, Fan F, Wang ZL. Theoretical comparison, equivalent transformation, and conjunction operations of electromagnetic induction generator and triboelectric nanogenerator for harvesting mechanical energy. *Adv. Mater*. 2014;26:3580-3591.

35. Jin L, Deng W, Su Y, et al. Self-powered wireless smart sensor based on maglev porous nanogenerator for train monitoring system. *Nano Energy*. 2017;38:185-192.

36. Quan T, Wang X, Wang ZL, Yang Y. Hybridized electromagnetic triboelectric nanogenerator for a self-powered electronic watch. *ACS Nano*. 2015;9:12301-12310.

37. Wang X, Wang S, Yang Y, Wang ZL. Hybridized electromagnetic triboelectric nanogenerator for scavenging air-flow energy to sustainably power temperature sensors. *ACS Nano*. 2015;9:4553-4562.

38. Zhang K, Wang X, Yang Y, Wang ZL. Hybridized electromagnetic triboelectric nanogenerator for scavenging biomechanical energy for sustainably powering wearable electronics. *ACS Nano*. 2015;9:3521-3529.

39. Jin L, Chen J, Zhang B, et al. Self-powered safety helmet based on hybridized nanogenerator for emergency. *ACS Nano*. 2016;10:7874-7881.

40. Zhang B, Chen J, Jin L, et al. Rotating-disk-based hybridized electromagnetic–triboelectric nanogenerator for sustainably powering wireless traffic volume sensors. *ACS Nano*. 2016;10:6241-6247.

41. Li Z, Chen J, Zhou J, et al. High-efficiency ramie fiber degumming and self-powered degumming wastewater treatment using triboelectric nanogenerator. *Nano Energy*. 2016;22:548-557.

42. Chen J, Yang J, Guo H, et al. Automatic mode transition enabled robust triboelectric nanogenerators. *ACS Nano*. 2015;9:12334-12343.

43. Chen J, Zhu G, Yang W, et al. Harmonic-resonator-based triboelectric nanogenerator as a sustainable power source and a self-powered active vibration sensor. *Adv. Mater*. 2013;25:6094-6099.

44. Xie Y, Wang S, Lin L, et al. Rotary triboelectric nanogenerator based on a hybridized mechanism for harvesting wind energy. *ACS Nano*. 2013;7:7119-7125.

45. Bai P, Zhu G, Lin Z-H, et al. Integrated multilayered triboelectric nanogenerator for harvesting biomechanical energy from human motions. *ACS Nano*. 2013;7:3713-3719.

46. Zhang B, Zhang L, Deng W, et al. Self-powered acceleration sensor based on liquid metal triboelectric nanogenerator for vibration monitoring. *ACS Nano*. 2017;11:7440-7446.

47. Saurenbach F, Wollmann D, Terris BD, Diaz AF. Force microscopy of ion containing polymer surfaces: morphology and charge structure. *Langmuir*. 1992;8:1199-1203.

48. Zhou YS, Liu Y, Zhu G, et al. In-situ quantitative study of nanoscale triboelectrification and patterning. *Nano Lett.* 2013;13:2771-2776.

49. Zhang H, Yang Y, Su Y, et al. Triboelectric nanogenerator as self-powered active sensors for detecting liquid/gaseous water/ethanol. *Nano Energy*. 2013;2:693-701.

50. Guo H, Chen J, Tian L, Leng Q, Xi Y, Hu C. Airflow-induced triboelectric nanogenerator as a self-powered sensor for detecting humidity and airflow Rate. *ACS Appl. Mater. Interfaces*. 2014;6:17184-17189.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**How to cite this article:** Cui X, Cao S, Guo R, et al. Building self-powered emergency electronics based on hybrid nanogenerators for field survival/rescue. *Energy Sci Eng*. 2020;8:574–581. [https://doi.org/10.1002/ese3.497](https://doi.org/10.1002/ese3.497)