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Review

Nanogenerator as new energy technology for self-powered intelligent transportation system

Long Jin[a], Binbin Zhang[a], Lei Zhang[a], Weiqing Yang[a,b,*]

[a] Key Laboratory of Advanced Technologies of Materials (Ministry of Education), School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, 610031, China

[b] State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu, 610031, China

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ABSTRACT

In recent years, the rapidly developed intelligent transportation system (ITS) is rendering safety and convenient life to human. However, the external power source with limited life is still a big technical bottleneck for further development of the wireless monitoring sensors in ITS. Fortunately, nanogenerator can not only harvest ambient environment energy during traffic carrier running process to power lots of arbitrarily distributed sensors of ITS, but also act as active sensor to realize self-powered wireless monitoring for ITS. This paper systematically reviews the development of nanogenerators, including piezoelectric nanogenerators and triboelectric nanogenerators, for self-powered technology in land-, water- and air-ITS, such as automobiles, trains, vessels and aircrafts, along with bridges, tunnels, highways and tracks. Meanwhile, some major achievements are summarized. Finally, perspective and remaining challenge are also discussed for further development of self-powered ITS.

1. Introduction

In human history, transportation allows human to know the world and promotes cultural communication, playing an indispensable role for human civilization. Benefiting from the development of transportation, human can go further both in distance and civilization [1]. In modern life, intelligent transportation system (ITS) is developed for human safety and convenience, especially in urban transportation network [2,3]. Sensors, as basic of ITS, are widely distributed for signal collection [4,5]. And in the whole system, big data and subsequent processing can come into play for transportation scheduling, which can be called intellectualization, only if sensors work. Thanks to the development of micro electronic technology, the smaller sensors have lower energy consumption. However, the power source (batteries or supercapacitors) for sensors is still life-limited. It's a huge project to frequently replace or recharge for a mount of arbitrarily distributed sensors. Meanwhile, the waste batteries bring a great impact on environment. On the other hand, traditional cable power supply shows a rapidly growing problem of complex wire arrangement owing to the increasing number of sensors. In this regard, self-powered technology is highly desirable and mandatory.

In fact, there are various energy sources during vehicle running process for harvesting, such as vibration energy, wind energy, impact energy and so on. Here, self-powered technology is to harvest these kinds of energy for sensors without external power source, solving the problem of complex wire arrangement. As an energy harvester, the piezoelectric nanogenerator (PENG) [6] was first presented in 2006 using zinc oxide (ZnO) nanowires (NWs), marking the beginning of self-powered technology. The principle can be concluded as coupling of piezoelectric and semiconducting properties, creating a strain field and charge separation across ZnO NW. And the rectifying characteristic of the Schottky barrier generates electrical current. After this work, many studies about enhancement [7–10] and application [11–17] of ZnO, as well as other piezoelectric materials, such as lead zirconate titanate (PZT) [18], and BaTiO3 (BTO) [19], were reported one after another. Then, by conjunction of triboelectrification and electrostatic induction, the triboelectric nanogenerator (TENG) was firstly invented in 2012 [20]. Up to now, TENGs have a very high area power density of 500 W/m^2, and the volume power density reaches 15 MW/m^3 [21]. In the last few years, TENGs have a fast development, including the vertical contact separation mode [22–25], the sliding mode [26–30], the single-electrode mode [31–35], and the freestanding triboelectric-layer mode [36–39]. Many studies have been reported for improvement in materials [40–47], output [48–54], stability [55–58], structure design [59–66], and applications [67–84]. Not only because of the high power density and efficiency, TENGs show great property and applicability for

* Corresponding author. Key Laboratory of Advanced Technologies of Materials (Ministry of Education), School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, 610031, China.

E-mail address: wqyang@swjtu.edu.cn (W. Yang).

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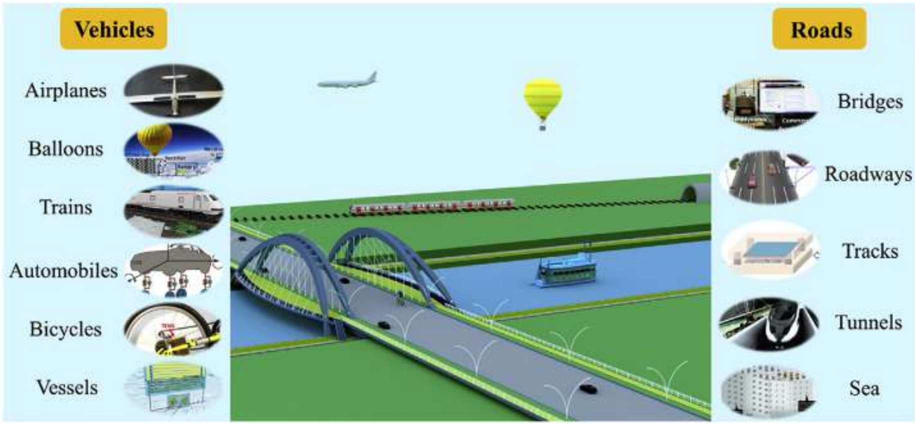

Fig. 1. Schematic diagram showing the main development of nanogenerators for self-powered technology in the field of intelligent transportation system. Vehicles: Airplanes [179]. Balloons [132]. Trains [116]. Automobiles [109]. Bicycles [120]. Vessels [126]. Roads: Bridges [140]. Highways [152]. Tracks [160]. Tunnels [144]. Sea [174].

wide adjustability in various environment. Especially, the unique light weight and high efficiency at variable frequency, which is common in modern transportation, will undoubtedly lead to tremendous potential in ITS.

Here, this review focuses on the development of nanogenerators for self-powered technology in land-, water- and air- ITS, including vehicles and roads. Fig. 1 illustrates the theme of this article, including several typical designs and applications in transportation. In the first part of this review, we summarized the applications of TENGs and PENGs for vehicles, including land vehicles (automobiles, trains, and bicycles), water vehicles (vessels), and air vehicles (airplanes). In the subsequent section, we elaborated on the intelligent roads by nanogenerators, including land roads (bridges, tunnels, highways and tracks), as well as water roads (typically sea). Finally, some perspectives and challenges about the future development and application of nanogenerators for ITS were discussed.

2. Nanogenerators for intelligent vehicles

Vehicles play an indispensable role in transportation system, because they are the carriers of passengers and cargos. Therefore, the safety of vehicles is always the research emphasis. Nevertheless, some parts of vehicles can't be monitored in real time, owing to the limitation of power and complex wire management. Combined with nanogenerators, components of vehicles can be improved to be self-powered, safer and more reliable, leading to vehicles intellectualization.

2.1. Land transport vehicles

2.1.1. Automobiles

Automobiles, as one of the most popular transportation, are widely used all over the world. With the development of intelligent automobiles, information collection is more and more important. However, sensors, as the information collector, need uninterrupted electric power to work and high accuracy to keep error as small as possible. In this case, nanogenerators can be power source and high sensitive sensors at the same time. Fig. 2a shows structure design of the PENG as a self-powered 3D acceleration sensor [85]. This design made it possible to measure vector acceleration in any direction. What's more, the individual sensor had high sensitivity of $2.405\,nA\,s^2\,m^{-1}$ and excellent stability of 97% remaining after 10000 cycles, owing to the unique piezoelectric material, Polyvinylidene Fluoride (PVDF) by high-pressure melt crystallization with a high β-phase crystallinity of 86.48%. As application, a collision was simulated for test of real-time collision monitoring and alert signal transmission. On the other hand, TENGs are also utilized as acceleration sensors. Different from the principle of PENGs, the output of TENGs relies on the sliding displacements [86]. Heo et al. presented an omnidirectional impact sensor using a TENG [87]. The structure design was a hemisphere with PMMA (polymethyl methacrylate) coated as triboelectric negative material. And the working principle was mainly the contact area change induced by the barycenter offset. It's similar to the work by Wu et al. [88].

Tires, as consumables, catch pretty attention on safety monitoring [89–91]. But the tire sensors are powered by life-limited batteries, hindering the intelligent development. For this problem, Qian et al. proposed a TENG to harvest rotation energy [92]. The periodic magnetic force made two parts of TENG contact and separate. Thus, the device had a high peak power of 22.3 mW. For the same purpose of rotation energy harvesting, Chen et al. proposed a free-rolling structure hybrid nanogenerator [93]. And it was demonstrated to power wireless sensors. Guo et al. utilized a direct method to harvest the rolling tire mechanical energy by arrays of compressible hexagonal-structured TENG [94]. Different from the contact-separate mode, TENGs of single-electrode mode can harvest tire energy by friction with ground [95,96]. Whereas, PENGs with thin thickness have a natural advantage when applied on tires. Hu et al. demonstrated the possibility for energy harvesting from automobile tire by integrating PENG onto the inner surface of bicycle tire [97]. Fig. 2b shows the tire shape change and experiment setup, inducing the electricity generating of ZnO. In this work, PENG was based on ZnO NWs for their flexibility. With the effective working area of $1.5\,cm \times 0.5\,cm$, the PENG had a maximum output power density of $70\,\mu W/cm^3$. In addition, the output changed with the increasing speed of the vehicle from $10\,m/s^2$ to $30\,m/s^2$, showing the potential as a self-powered speed sensor.

Besides tires, engines are essential as the core component of automobiles. Zhang et al. presented a highly sensitive acceleration sensor based on a TENG [98]. With the component of liquid metal droplet and nanofiber-networked PVDF film by electrostatic spinning (Fig. 2c), the device had a small size but high open-circuit voltage and short-circuit current, reaching up to 15.5 V and 300 nA at $60\,m/s^2$. It's worth mentioning that PVDF nanofibers by electrostatic spinning is proved outstanding in performance of both piezoelectricity [99] and triboelectricity [100]. When applied on the automobile engine, the sensor exhibited extreme sensitivity with different states of start, running, and stop. In addition, vibration is very common on many components of automobiles. Xu et al. designed a spring structure TENG to harvest the vibration on automobile [101]. At the same time, the device could also be used as a vibration sensor.

As one of environmental pollution sources, tail gas is always a hot topic. Shen et al. presented a self-powered vehicle emission testing system by coupling a TENG and a resistance-type gas sensor [102]. The working principle was based on the different output with various external load resistances. They tested the output voltage with NO_2 concentrations ranging from 0 to 100 ppm, as well as different relative humidity conditions with 100 ppm NO_2. Finally, 3 series-connection light-emitting diodes (LEDs) were connected in the circuit of the TENG with a gas sensor, and the self-powered test system was proposed as Fig. 2d. LEDs could be lighted up when NO_2 was injected, which could

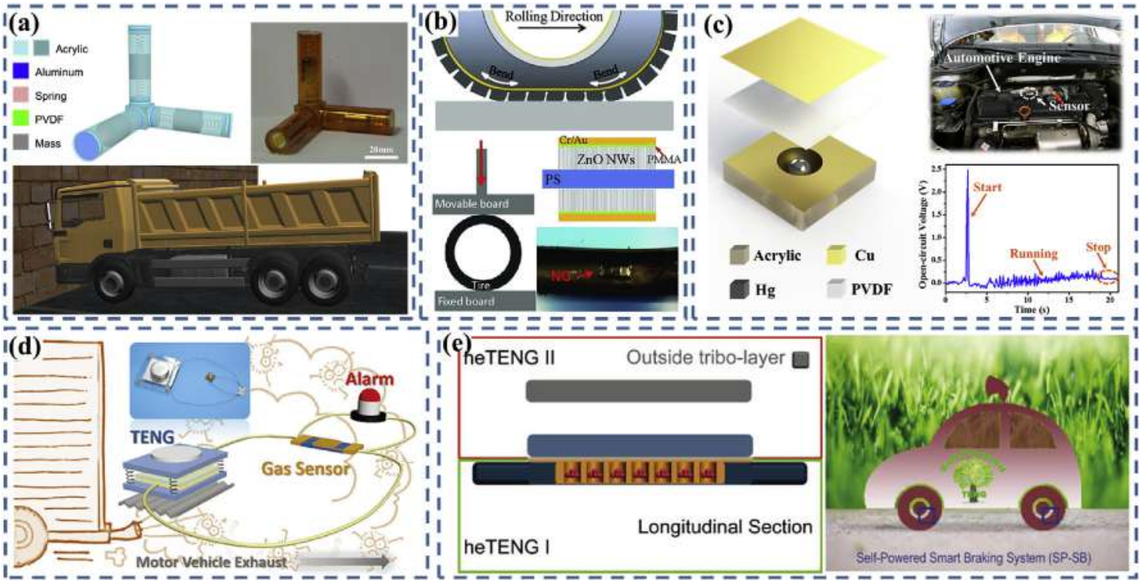

Fig. 2. Applications of nanogenerator in automobile. (a) Structure design and photograph of the fabricated sensor for vehicle collision alert [85].
(b) ZnO based nanogenerator is fixed on the inner tire to harvest energy [97].
(c) Self-powered acceleration sensor is used to monitor process of engine for start, running and stop [98].
(d) Schematic illustration of the self-powered vehicle emission testing system [102].
(e) Diagram of two TENGs and application as a self-powered braking system [109].

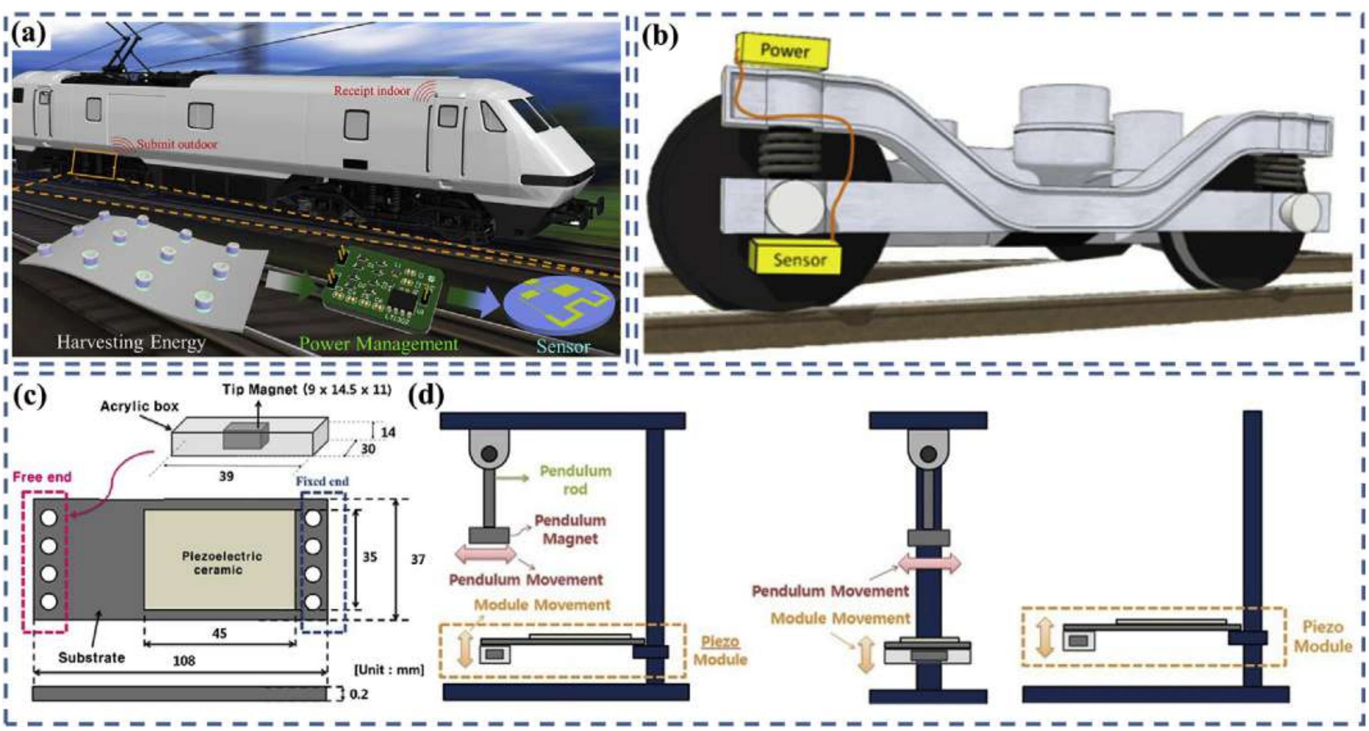

Fig. 3. Energy harvesting technology for train. (a) Self-powered system including TENG, power management and a sensor for train monitoring [116].
(b) Placement of energy harvester on the bogie for a sensor [118].
(c) Design and dimensions of the energy harvesting module. (d) Pendulum moves in the X-direction, Y-direction, vertical vibration [119].

be regarded as an alarm. Despite of the gas sensor, many studies have been reported that TENG can be utilized as removal of particulate matter (PM) [103–107]. Han et al. firstly applied a TENG as a filter on automobiles, making the system self-powered [108]. And the result showed excellent performance with more than 95.5% of removed PM 2.5.

As the critical supporting part of automobiles, brake pads play an important role in automobile safety system. At the same time, braking energy is abundant as supplement of automobile energy. Wen et al. presented a harsh-environmental-resistant TENG, which could be directly used as the brake pad [109]. It was made by hybridizing micro–nanocomposite with a good wear resistance that the mean dynamic friction coefficient was ~0.69 μm at low-friction force of about 8.1 N and room temperature. Also, the high-temperature tolerance was excellent (temperature range of −30 to 550 °C) in case of the heat when braking. Based on the wear-resistant triboelectric materials, a harsh-

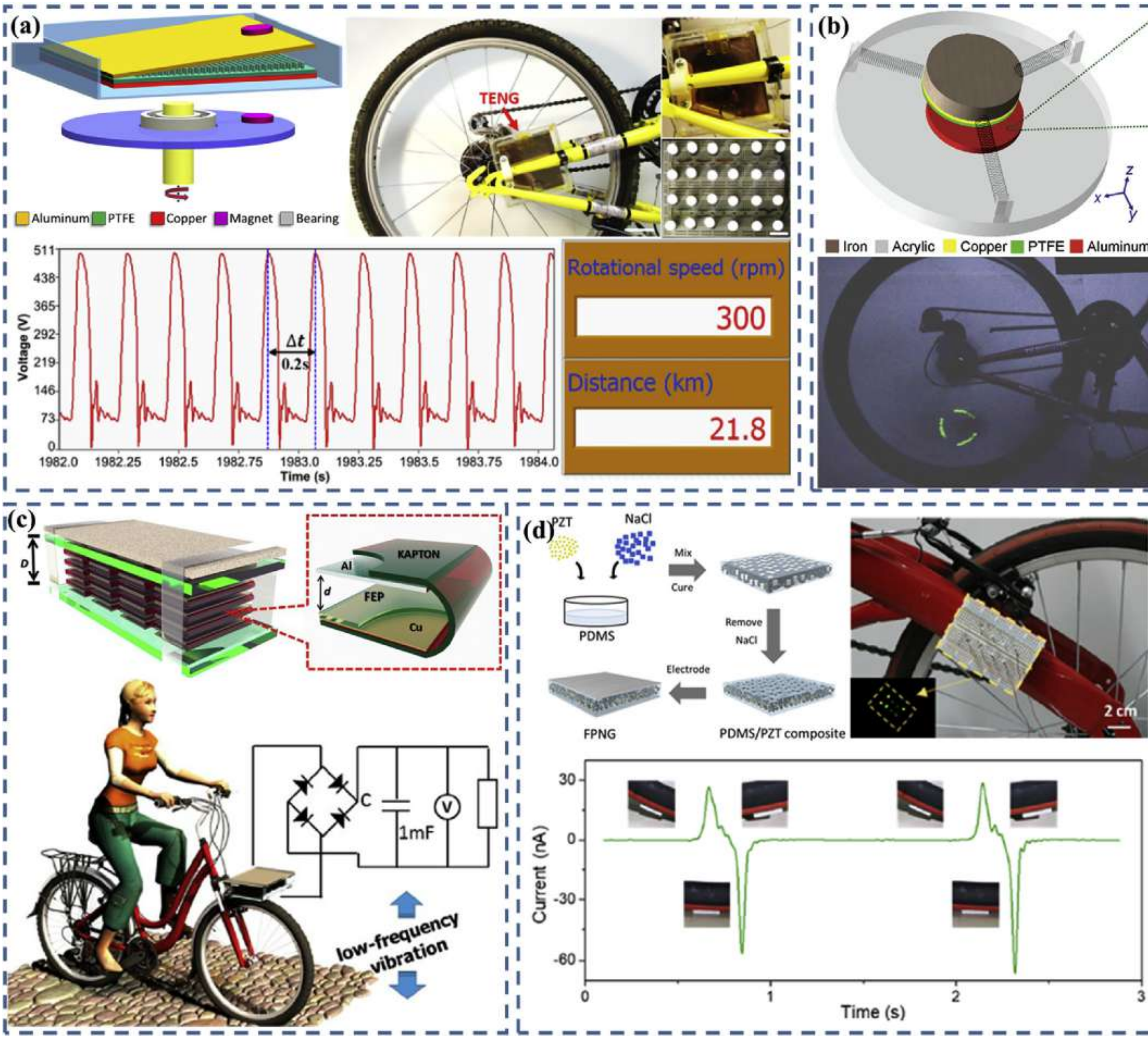

Fig. 4. Nanogenerator applied on bicycle for energy harvesting. (a) Automatic transition TENG applied on bicycle to harvest rotation energy and monitor rotational speed [120].
(b) The designed 3D-TENG applied on the rotating bicycle wheel [23].
(c) The multiunit TENG to harvest vibration energy on a bicycle [121].
(d) Fabrication process of the porous PENG and its application to harvest energy when fixed on the bicycle tire [122].

environmental TENG (heTENG) was designed with good performance, consisting of a freestanding mode heTENG-I and a single electrode mode heTENG-II, shown in Fig. 2e. Under engine speed of 4000 r/min and a frequency around 1 Hz, output performance of 221 V, 27.9 μA/cm [2], and 33.4 nC/cm^2 could be produced. And the self-powered smart brake system with the device, a diode-bridge, a 1 μF capacitor, a switch, and a wireless transmitter could automatically provide exact early-warning. Another study also reported the application of a TENG in brake system [110]. But the TENG was free-standing mode to harvest rotation energy for the self-powered Hall vehicle sensor. Meng et al. reported a novel idea about driver behavior monitoring by TENGs [111], which extended the application to drivers. As can be seen, the applications of nanogenerators for automobiles are not only limited to automobile parts, but derivative parts (for example, driver behavior) begin to be emphasized. This trend may expedite the intelligent development of automobiles.

2.1.2. *Trains*

Trains run on the tracks, usually faster than automobiles. Hence, the vibration is more violent and general on trains [112–115]. Jin et al. reported a maglev porous nanogenerator (MPNG) to harvest vibration energy of bogie for a wireless smart sensor [116]. The schematic illustration can be seen in Fig. 3a. The ingenious maglev structure made it less impact energy and more energy for electric energy transform. MPNG consisted of a TENG and an electromagnetic generator (EMG), which could deliver peak power density of 0.34 mW/g at 50 MΩ and 0.12 mW/g at 700 Ω, respectively. The electricity could be stored in supercapacitors or Li-ion batteries through the power management. Finally, the MPNG was demonstrated working well when connected with a wireless temperature and humidity sensor. What's more, MPNG had a small size and light weight, which could be packaged as arrays for more energy harvesting and different applications.

Not only TENGs, PENGs have good performance in vibration energy harvesting. The cantilever structure is widely used as a typical vibration energy harvesting structure, even in the novel ZnO NWs [117]. Deng et al. improved it by a tuning fork-shaped PENG, and got optimized power at low frequency [7]. Ortiz et al. used PZT, which had excellent piezoelectricity, to harvest vibration energy to power bogie-mounted sensors for wireless communication (Fig. 3b) [118]. Finally, the whole self-powered system was mounted on the bogie and tested, demonstrating the possibility to harvest vibration energy in bogies.

Cho et al. designed a piezoelectric energy harvesting system by magnetic pendulum movement (PEH-MPM) [119]. The piezoelectric module was designed as cantilever beam with PZT, but the free end was added with a tip magnet (Fig. 3c). Also, a magnet was added on the pendulum rod. And then, the PEH-MPM could be placed on train. As shown in Fig. 3d, when there was movement on the X-direction, the pendulum rod could move in X-direction. Because of attraction and repulsion between two magnets, the piezo module had a deformation. Thus, electricity could be generated. Similarly, when the rod moved in Y-direction, electricity could be also generated. If there was no pendulum rod, the tip magnet could act as a mass. It's a classical cantilever beam, which can generate electricity when there is vibration in Z-direction. In conclusion, it had maximum average power density of 40.24 μW/cm^3, supporting recording system for vibration and acceleration data of the train. Compared with automobiles, trains show obvious insufficiency in intellectualization. The core components of trains, such as bogies and wheels, are in urgent need of real-time and self-powered monitoring.

2.1.3. Bicycles

Bicycles are very popular and environmental friendly for a short distance. But the intelligent development is still slow owing to the limited power source for electronics in bicycles. Fortunately, when people ride bicycles, there're vibration energy, rotation energy, and wind energy, which can be harvested by nanogenerators. Chen et al. presented an automatic transition TENG (AT-TENG) for rotation energy harvesting [120]. Different from traditional TENGs for rotation energy harvesting, this device could convert the in-plane sliding electrification into a contact-separation working mode (Fig. 4a), ensuring the high output performance and robustness at the same time. The authors also investigated the output on different rotation speed, and found that higher speed could lead to non-contact working state while lower speed could lead to contact working state. It's an inherent characteristic, because the magnetic repulsive force has a shorter exertion time at higher speed. As a result, it could deliver an open-circuit voltage up to 530 V with short-circuit current of 0.26 mA at a rotation rate less than 240 rpm. When AT-TENG was applied on a bicycle and a human rides naturally, the as-harvested energy lighted up 24 spot lights simultaneously. On the other hand, due to the unique working mode, AT-TENG could be utilized as a self-powered real-time speedometer for moving speed and traveled distance with ultrahigh measurement accuracy.

Besides rotation energy, Yang et al. reported a 3D-TENG to harvest vibration energy and rotation energy [23]. The core of this device was a mobile iron mass suspended by three identical springs, enabling it to have two working mechanism, contact separate mode and sliding mode, as shown in Fig. 4b. Wang et al. designed multiunit TENG, which could harvest ambient vibration energy over a wide frequency range [121]. In this work, TENG had a small volume of 5.7 × 5.2 × 1.5 cm and light weight of 45 g, owing to the zigzag structure (Fig. 4c) for 15 layers. But its output power density was as high as 102 W/m^3 at 7 Hz. What's more, it maintained a stable current output from 5 to 25 Hz, showing the potential for broad applications. When applied on a bicycle, the vibration energy from bumping could be harvested for sensors to monitor the environmental temperature, humidity, and speed through a power management unit. When passing a gentle road bumping for 90 m, the energy harvested by the TENG could charge a 1 mF Al electrolytic capacitor from 0 to 2.3 V. Therefore, sensors could be continuously powered while riding a bicycle.

Flexible nanogenerators usually have adaptability in shape, and fit for curvature of tire. Ma et al. presented a flexible porous nanogenerator (FPNG) by the conjunction of ferroelectricity and piezoelectricity [122]. PZT and salt were added in polydimethylsiloxane (PDMS). After cured, salt was removed and the composite was prepared. Finally, after polarization and preparing electrode on it, a FPNG was prepared. The detailed process can be seen in Fig. 4d. With a very small dimension of 2 × 2 × 0.3 cm^3, FPNG had open-circuit voltage and short-circuit current of 29 V and 116 nA, respectively. As can be seen, the FPNG fit the bicycle tire well, showing the strong adaptability in shape. When it rolled, electricity could be generated due to the deformation of the FPNG. The energy harvesting method is similar to automobile tire. Based on the studies, bicycles with nanogenerators have great potential to monitor their own states and transmit signals, which is the basic for intelligent development.

Land transport vehicles play a crucial role in our daily life. With the rapid development of big data and artificial intelligence (AI) technology, automobiles and trains have trend to be more intelligent. In this respect, sensors will get self-powered and real-time for information transmission when applied with nanogenerators. On the other hand, bicycles can be taken into consideration as an important factor in urban intelligent transportation network when combined with nanogenerators, improving safety of both bicycle riders and other drivers. Because the state of bicycles can be monitored in real time and alerts others for accident prevention.

2.2. Water transport vehicles

Similar to automobiles and trains, vessels are driven by big power source while their small distributed sensors need continuous but small power. Furthermore, vessels are special because the environment of water is terribly destructive for cable power supply, but contains a lot of energy at the same time. Zhao et al. presented a solid-liquid interfacing TENG to convert random water wave energy into electricity [123]. The structure design can be seen in Fig. 5a. The electrodes were connected with anode and cathode by p-n junctions. So the output was direct current (DC) rather than alternating current (AC), which made rectifier unnecessary. The area of 100 × 70 mm^2 could generate short-circuit current of 13.5 μA and peak power of 1.03 mW at a water wave height of 12 cm. By investigating the relationship between output and water wave type, the authors found that TENG could harvest the energy from random and dynamic water wave with a rough water level and smooth water wave with an almost linear water level very well at the same time. Finally, a 22 μF capacitor was charged to 5.8 V within 67s. After a wireless transmitter triggered, the voltage dropped to 1.4 V. And then, it was charged for another transmission for only 53s. Moreover, solid-liquid interfacing TENG can be also utilized as a robust and sensitive indicator for detecting the water level [124], which is self-powered, robust, and accurate for extensive applications in marine industry.

The complex environment of water has not only energy, but also many microbes. They are harmful to the parts of vessels underwater, block pipes, and even boost engine stress. Instead of coating materials to protect, Long et al. used surface electric disturbance by TENG to realize the effect of anti-biofouling [125] as shown in Fig. 5b. Similarly, Zhao et al. investigated oscillation of electric potential for antifouling on insulating surface [126]. Also, TENGs are the best choice for the ability to harvest water wave energy. In this work, rectifying chips were added in the TENG. Thus, the output part could be separated into anode and cathode, as shown in Fig. 5c. As a contrast, the anode and cathode were being submerged in the culture solution with a high concentration of *E. coli* for 24 h. As a result, the anti-adhesion efficiencies reached up to 99.6% and 99.3%, respectively. However, external DC (3 V) and AC (110 V) could only give the anti-adhesion efficiencies of 83.9% and

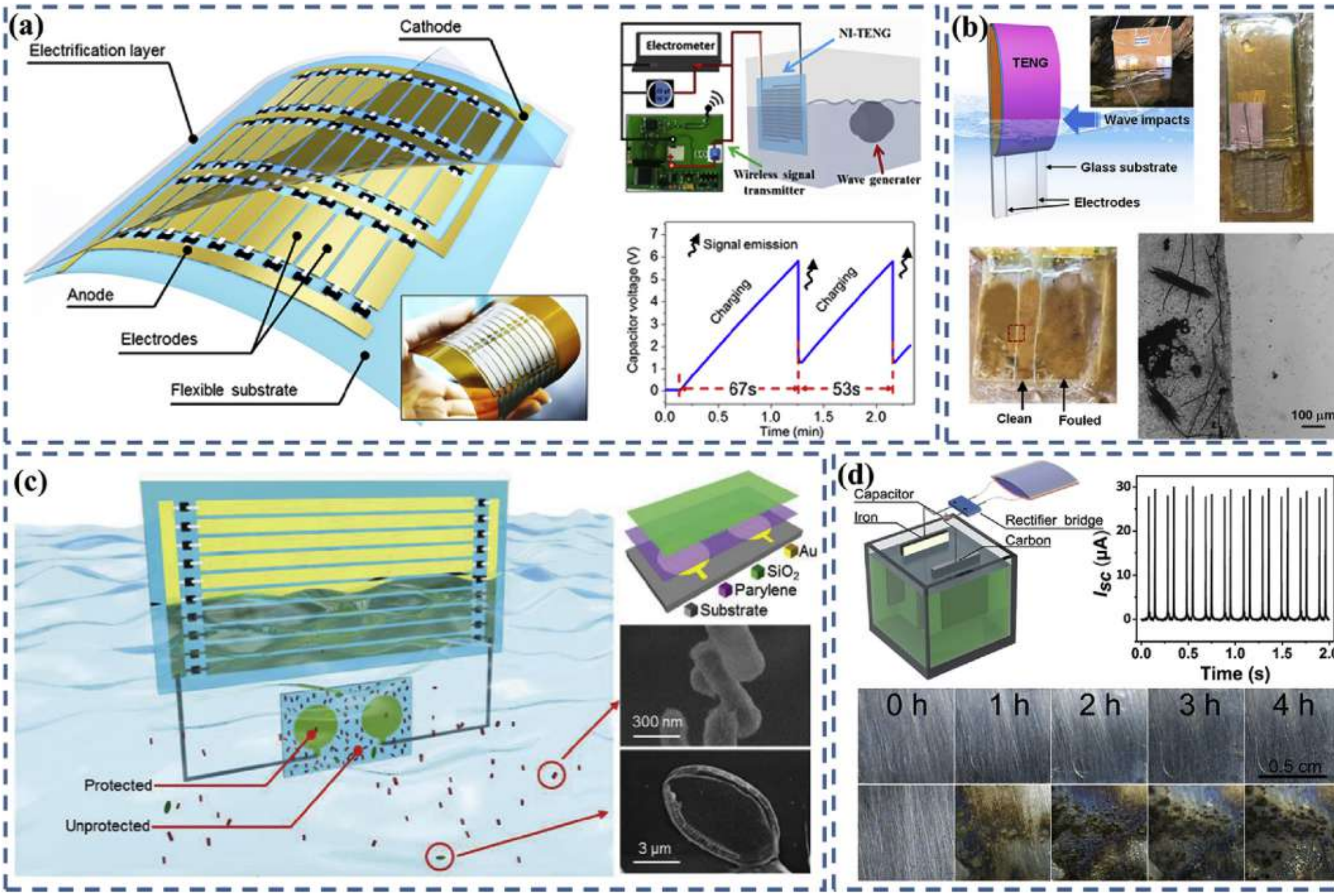

Fig. 5. TENG works on the water for energy harvesting and anti-corrosion. (a) The designed TENG with DC output is used to harvest wave energy for powering a wireless signal transmitter [123].
(b) The water-driven anti-biofouling system by TENG at the shore of lake [125].
(c) The anti-adhesion system setup by TENG with p-n junction [126].
(d) The system of cathodic protection powered by TENG [127].

95.5%, respectively, demonstrating the superiority of TENGs. In the same way, the anti-adhesion efficiency against Nitzschia Sp. was proved as high as 94.6%. Moreover, investigating the effect of surface roughness showed that roughened surface with micro or nano structures had a further 75% enhancement on anti-adhesion. This work has more comparison and detailed data, fully demonstrating its potential for intelligent vessel in Antifouling.

Despite of microbes, water can easily corrode steels, which are basic materials for vessels. Feng et al. presented a paper-based TENG for self-powered anticorrosion. In this work, paper and PVDF acted as triboelectric materials [127]. After modification of paper by polydopamine, the short-circuit current and open-circuit voltage could reach up to 30 μA and 1000 V, respectively. And the charge density increased obviously to 76 $\mu C\, m^{-2}$ from 24 $\mu C\, m^{-2}$. As can be seen in Fig 5d, a piece of A3 steel of $0.7 \times 0.7\ cm^2$ and carbon electrode were connected to TENG through a rectifier bridge and capacitor of 1.2 μF. To imitate the seawater corrosion condition, 3.5% NaCl aqueous solution was added. Then the TENG started to work. As time goes by, the surface of steel with TENG protection had little change, while the steel without protection was corroded badly. On the other hand, an investigation of antifouling showed it had good antifouling properties for both dunaliella and navicula. Guo et al. also demonstrated excellent metal corrosion prevention effect by TENGs [128,129]. Subsequently, the work in NaCl solution by Chen et al. revealed the electrochemical process by TENG [130]. Hence, TENGs are great for antifouling and no external power is needed. This self-powered device makes vessels smart, promoting the intelligent development of water transport vehicles.

Vessels, as water transport vehicles, are special among the transport vehicles, which are pretty suitable for self-powered technology, because of the environment of water. On one hand, self-powered device can be wireless both in signal transmission and power supply, leading to no damage to the electrical power system of vessels when they are destroyed by water. On the other hand, the energy in water is abundant and easy to be harvested by TENGs. Apart from energy harvesting, TENGs' property of high voltage has excellent anti-biofouling and anticorrosion effect exactly. It's a self-powered technology with high efficiency and no danger, paving a way to water transport vehicle intelligent protection.

2.3. Air transport vehicles

Aircrafts usually run in the upper air, where the wind has fast speed, high stability, and perenniality [131]. The abundant wind energy is difficult for traditional wind turbine generators. To solve this problem, Zhao et al. developed a freestanding flag-type TENG for wind energy harvesting [132]. As shown in Fig. 6a, the Kapton film-sandwiched Cu belts and Ni belts with gaps between them consisted a contact-separate TENG. At a wind speed of 22 m/s, the open-circuit voltage and short-circuit current could reach up to ~40 V and ~30 μA, respectively. And the output peak power density of 135 mW/kg were tested at 6.5 MΩ. In addition, the output rose with the increasing wind speed, according to the research. For the ultimate purpose of powering electronics, a capacitor of 4.7 μF was charged to 8.1 V by three TENGs in parallel within about 10s, demonstrating the charge ability. Because of its freestanding

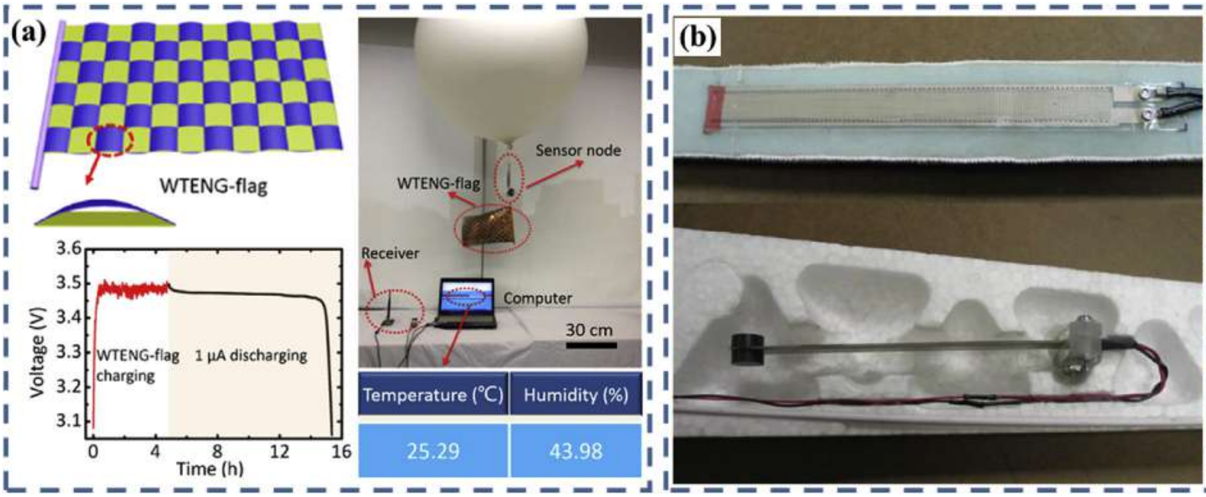

Fig. 6. Energy harvesting application on balloon and unmanned aerial vehicles. (a) The fabricated TENG including nickel and Kapton is used to harvest energy for wireless sensor node [132].
(b) Vibration energy harvester by piezoelectric patch placed on wing and in the fuselage [179].

2D design, any directions of wind energy could be harvested without obvious difference in output current. It's a big advantage for wind energy harvester. Finally, the authors designed a demo for harvesting high-altitude wind energy to power wireless sensor node. The wireless sensor was powered and transmitted signals to computer. And the condition of temperature and humidity could be measured. With the help of nanogenerators, the traditional balloon has small electrical power source and can transmit signals, exhibiting the first step to intelligent development. We can imagine a balloon carrying people with the TENG flag. If there's an accident, the electric energy can be used for emergency help.

Anton et al. investigated the possibility of harvesting vibration energy in the unmanned aerial vehicle (UAV) [133]. Usually, airplanes have higher speed rather than balloons, resulting in impossibility for the TENG flag. What's more, drag reducing is the priority in airplane engineering. On the other hand, vibration exists when airplanes are flying, which is bad for safety but good to be harvested exactly. In this work, the wing spar and fuselage were made by fiberglass, as the demo. Piezoelectric fiber composite (PFC) was placed on the wing, as shown in Fig. 6b. When there was vibration, the wing and the tightly attached PFC had deformation and electricity could be generated. PFC was also designed as cantilever structure in the fuselage, because the fuselage had vibration but little deformation. It's a classical solution to solve this kind of problems in the field of energy harvesting. As a result, the average power output of the cantilever PFC and the PFC attached to the wing was calculated as 24.0 μW and 10.1 μW, respectively. In addition, EH300 energy harvesting chip was applied for power management. The result showed that during a 13 min flight, the piezoelectric patches charged the EH300 4.6 mJ internal capacitor to 70% capacity. Although this work is only for UAV, energy harvesting shows great potential for all kinds of airplanes, which can be improved to be more intelligent and safer. Le et al. summarized energy harvesting for structural health monitoring in aeronautical applications, fully demonstrating the possibility and advantages of self-powered technology [134].

Although there's no practical application on real aircrafts, the previous studies have demonstrated the great possibility to harvest wind and vibration energy. As a matter of fact, turbine blades are desperately in need of real-time monitoring but it's unreachable for traditional cable power supply and signal transmission. Based on advanced TENGs [135] and PENGs [136] in high-temperature environment, the intellectualization of airplane critical component will come true soon.

3. Nanogenerators for intelligent roads

Roads are the support for vehicles. Hence, the condition of roads directly affects the driving safety. Although intelligent roads, aimed at improving the safety and convenience of driving, have a rapid development, the cost is staggering. What's more, some special roads, such as bridges and tunnels, still need further intelligent development. In this regard, nanogenerators can contribute significantly in the field of real-time sensors and reduce the cost for future intelligent improvement. Here, we introduced some kinds of roads combined with nanogenerators for intellectualization.

3.1. Land roads

3.1.1. Bridges

Bridges make pedestrians, automobiles and trains span physical obstacles, leading to time saving and economic benefit. Usually, the physical obstacles are dangerous, such as water, and valley. Therefore, the bridge safety matters a lot to driving safety. However, the traditional manual detection method increases the risk of workers owing to the dangerous environment when compared with real-time monitoring. It brings us to another problem that the limit power source of real-time sensors. Here, nanogenerators give us a fantastic solution by self-powered technology. In 2012, Pan et al. presented an optical fiber-based 3D hybrid cell (HC), including dye-sensitized solar cell (DSSC) and a PENG [137]. As a demo, HC was applied beneath the bridge with a diameter of 500 μm and a length of 2 cm, delivering 7.65 μA and 3.3 V, as can be seen in Fig. 7a. Detailedly, DSSC consisted of optical fiber, seed layer, dye-coated ZnO NWs and electrolyte, as a solar energy harvester. Sun light could enter the optical fiber and reflect inside for many times. Then, it could be harvested as the working principle of Fig. 7b.

Maruccio et al. applied PVDF nanofibers for structural health monitoring of a cable-stayed bridge [138]. Only polar β-phase showed piezoelectricity rather than non-polar α-phase (Fig. 7c). The authors presented a device by PVDF with opposite polarities tactfully, resulting in enhancement of output. After analysis, 6 identified modes of the bridge deck were applied. With regard to output, different cables with horizontal and vertical direction were different. With the length of 30 mm, width of 10 mm, tip-mass of 25 g, and resistance of 10 kΩ, the device can deliver electric energy of 1.217 mJ could be obtained from central cable in horizontal direction, which was the highest. While the longest cable in horizontal direction could only generate 0.014 mJ. In addition, the test time is 50 s. At the same time, the output of PVDF film

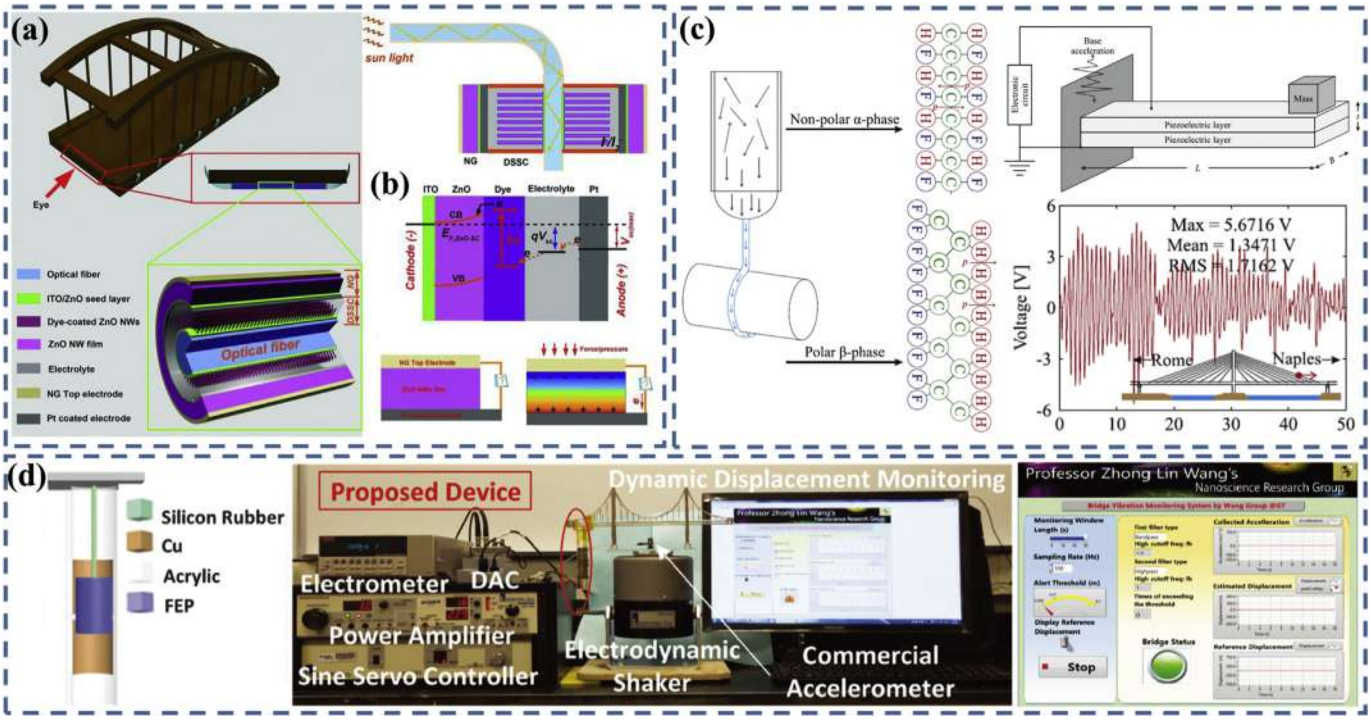

Fig. 7. Self-powered bridge system based on nanogenerator. (a) Bridge as a demonstration for the self-powered nanosystem by hybrid cell, including a solar cell and ZnO NWs based PENG. (b) Working principle diagram of the solar cell and PENG [137].(c) Bimorph-structure energy harvester by electrospun PVDF nanofibers is used for bridge state monitoring [138].
(d) The typical free-standing mode of TENG as an accelerometer for dynamic bridge vibration monitoring system [140].

was also measured. It's worth noting that the output of PVDF nanofibers were almost double that of PVDF film at the same condition. This result fully proves the excellent performance of nano materials. In this regard, nanogenerators have significant advantages.

Despite of harvesting energy, nanogenerators show good performance as an active sensor [117,139]. Especially, TENGs have high voltage output owing to the unique working principle. Yu et al. utilized TENG as an accelerometer to monitor the health of bridge [140]. As shown in Fig. 7d, it was a free-standing TENG consisting of copper and Fluorinated Ethylene Propylene (FEP). Silicon rubber was highly stretchable for movement of FEP and all the parts were covered in an acrylic tube. Firstly, the relationship between open-circuit voltage of the two electrodes and motion displacement of inertial mass was proved linear, which is basic for quantitative sensing parameters. For more visualization, a dynamic displacement monitoring software interface was developed by LabVIEW 2016, showing the value of sampling rate, the curves of collected acceleration, estimated displacement and reference displacement. It's intelligent that an alarm signal will be given if the displacement is continuously above the threshold. As a sensor, it had a high sensitivity of 0.391 $V\,s^2\,m^{-1}$. What's more, the relationship between output and acceleration was linear with a correlation coefficient of 0.975. Finally, the authors compared proposed TENG with a commercial piezoelectric acceleration sensor. The result demonstrated the excellent performance in low vibration frequency. So nanogenerators are not only a kind of good energy harvester, but also an excellent active sensor.

Intelligent monitoring is the core emphasis of intelligent bridges. And possibility of harvesting energy for sensors power on bridge is fully demonstrated by previous studies. In this condition, self-powered sensor is the appealing strategy to assess the state of bridges, leading to scalability, minimum interference and real-time monitoring. It's a significant step on intelligent development of bridge. Meanwhile, TENGs have a sharp sense in vibration monitoring.

3.1.2. Tunnels

Tunnels are shortcut to cross a high mountain by puncturing it. Also some tunnels are underground in cities to reduce traffic congestion. However, it's dark in the tunnel and the mechanical structure needs to be detected. What's worse, many tunnels are constructed in desolate places, increasing the difficulty for detection and power supply. Zhang et al. reported a self-powered active wireless traffic volume sensor by using a rotating-disk-based hybridized nanogenerator [141]. The hybridized nanogenerator was made by two parts, a single-electrode TENG and an EMG, which provided power for wireless traffic volume sensing system, as shown in Fig. 8a. As the same with enhancement by other studies [142,143], nanowires were processed on surface of PTFE for TENG by reactive ion etching. In addition, nanopores were created on the surface of aluminum triboelectric layer for more contact area. As a power source, the TENG part could provide instantaneous peak power density of 10.8 W/m^3 at a load resistance of 50 MΩ, while a volume output power density of 51.5 W/m^3 could be obtained at 400 MΩ from EMG part. After power management consisting of transformer and rectifier, the hybrid nanogenerator could power the wireless transmitter and the receiver showed the number of passing vehicles. In this work, the energy is from wind when vehicles pass by. And the tunnel is relatively closed. This kind of detection method is fit for tunnels, because the wind energy from passing vehicles is strong and the external effect is small.

Aimed at the great demand for electricity in the manmade long tunnels, Bian et al. proposed a bionic TENG tree (Fig. 8b) [144]. The TENG tree had two parts, leaf cell and stem cell. And the leaf-TENG had an elliptical shape like a natural leaf. When there is wind, the leaves will contact and separate, which can generate electricity. The stem-TENG has a structure of column encased in four soft slats like a stem. When there is wind, the soft slats will deform, resulting in contacting and separating with core. Thus, electricity can be obtained. At the wind speed of 17 m/s, leaf-TENG had open-circuit voltage of 260 V and short-circuit current of 37 μA, while stem-TENG had open-circuit voltage of

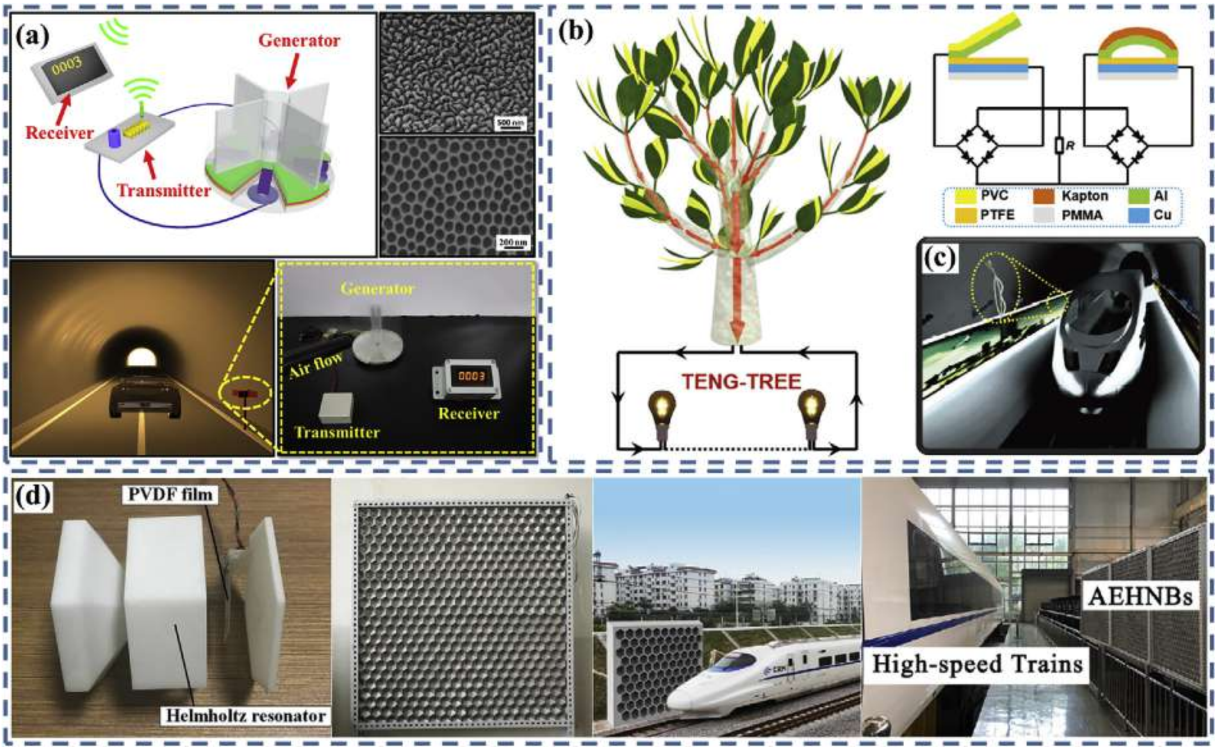

Fig. 8. Potential and application on tunnel as a sensor or energy harvester. (a) The wireless traffic volume sensing system by a TENG and an EMG [141]. (b) Diagram of TENG tree with leaf-TENG and stem-TENG. (c) Schematic diagram of TENG tree applied in the tunnel to power the advertising illumination [144]. (d) An energy harvesting unit including the Helmholtz resonator with PVDF film and its application to harvest acoustic energy by running high-speed train [145].

320 V and short-circuit current of 26 μA. By rectification, leaf-TENG and stem-TENG connected in parallel as a TENG tree could generate voltage of 330 V and current of 59.6 μA. Also, the maximum output power reached up to 3.6 mW at the matched resistance of 60 MΩ and wind speed of 11 m/s. As a result, 145 LEDs could be lighted up by harvesting wind energy. Fig. 8c is the schematic diagram of TENG tree for advertising illumination in the tunnel. Another work showed a renewable low-frequency acoustic energy harvesting noise barrier (AEHNB) using a Helmholtz resonator [145]. In this work, a PVDF film was designed as cantilever structure and fixed on a hexagonal prisms cavity, as shown in Fig. 8d. It's worth noting that the tunnel is a relatively closed environment, where the noise is not easy to spread around. The noise is a kind of energy and may be harmful to the tunnel. So this work is foresighted for noise energy harvesting and an important reference for tunnel's related work.

Tunnels are special among land transportations because of the enclosed environment and desolate building place. According to the previous studies, this special condition makes it in more need of and more suitable to self-powered technology. In detail, the enclosed environment can maintain more wind and noise energy for nanogenerators to harvest, while the desolate building place needs more electricity energy to power sensors because of the high maintenance cost and risk for workers.

3.1.3. Highways

Highways are the most common roads in our daily life, supporting automobiles and bicycles to get around for a short-distance trip. Intelligent road is a key part of ITS, leading to safety and convenience. Whereas, electronics in current intelligent road are usually maintained by people and supplied by cable, leading to increasing economic cost. Askari et al. proposed a hybridized electromagnetic-triboelectric generator consisting of TENGs and EMGs for energy harvesting [146]. The hybridized nanogenerator is designed into a speed bumper. When vehicles passed by, the mechanical load could be transformed into electricity (Fig. 9a). The detailed structure shows that PTFE film could move forward and backward between aluminum films, which is a typical free-standing TENG. On the other hand, EMG could harvest energy by magnetic flux change of the coil, owing to the movement of magnet. As a result, the result showed that the better work frequency of TENG was below 0.5 Hz, while the EMG had a better performance at a frequency over 0.5 Hz. The truth that TENG has a better performance at low frequency is demonstrated in many studies [147–149]. And the reason has been explained by Maxwell's displacement current [150]. Finally, the TENG and the EMG were used to charge a capacitor of 40 μF. Here, the advantage of hybrid nanogenerator is fully obvious. The TENG can charge it to a high voltage but takes a long time, while the EMG can charge it at a short time but the voltage is low. After hybridization, the capacitor can be charged to a high voltage and takes a short time. As a self-powered device, it has great potential for intelligent traffic monitoring by providing online traffic information. With similar application, another work about TENGs for caution system of vehicle parking is reported by Zhang et al. [151].

Smart sensing system is basic for ITS, and the wind energy induced by vehicles can act as a power source. In view of TENG's great performance in wind energy harvesting, it's a good choice. Wang et al. presented a smart network node based on hybrid nanogenerator [152]. The hybrid nanogenerator could harvest wind energy by flag-like TENGs and solar energy by a solar cell. The schematic can be seen in Fig. 9b. What's more, the relationship between output and wind speed was fitted linearly, which had potential for wind speed sensing. The solar cell had a continuous voltage output but low, while it was high for TENG but intermittent. Therefore, the hybrid device had much higher output after combining them. And a Li-ion battery of 10 mAh was charged by it to 2.7 V within only 540s. A wireless sensor could transmit signals by using the electricity harvested from the hybrid nanogenerator and a station could receive the signals elsewhere. In this work, the sensor was to monitor the temperature and a computer could receive the data by ZigBee module.

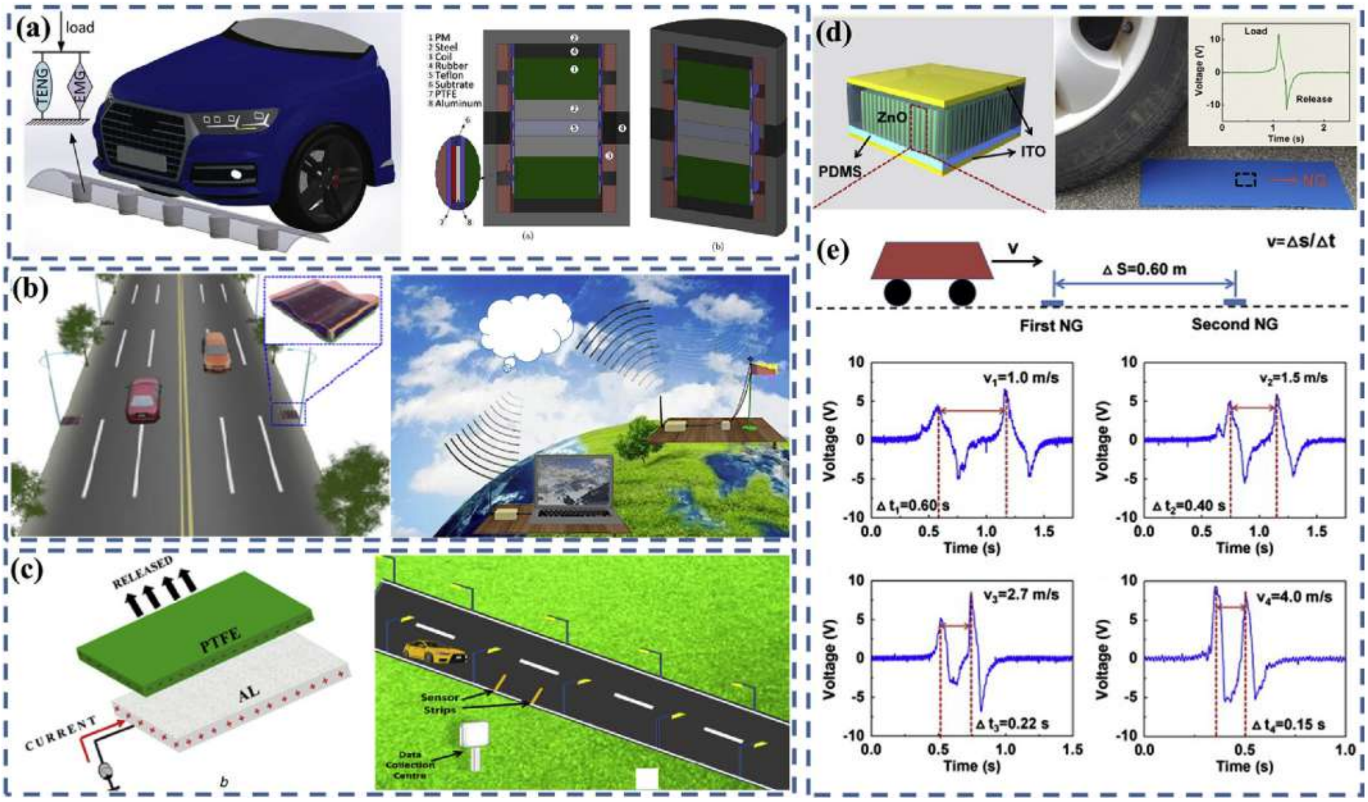

Fig. 9. Applications of nanogenerator applied as a sensor or energy harvester in highway. (a) TENG and EMG as a hybrid nanogenerator applied in the speed bumper [146].
(b) Schematic illustration of hybrid nanogenerator as wind energy harvester for intelligent traffic system [152].
(c) Single-electrode TENGs applied in the highway as sensor to monitor the passing vehicle speed [153].
(d) ZnO NWs based PENG is fixed on the road for automobile tire pressing. (e) The principle of measuring automobile speed by time difference of two PENGs and analysis of automobile speed. Calculated speed is 1.0, 1.5, 2.7, 4.0 m/s [154].

Vehicle speed monitoring on road is a key part of transportation system. Intelligent traffic monitoring relieves the road side traffic police. However, commercial speed measurement techniques are usually expensive and difficult to maintain. With this regard, the TENG is a good choice to solve this problem. Different from wind driven, a low-cost triboelectric sensor was presented by Yadav et al. [153] As shown in Fig. 9c, TENG had a single electrode mode with PTFE and aluminum as triboelectric materials. The result showed the accuracy was over 95% for vehicle speed measurement. After all, it's just a prototype, because many factors may affect the output of TENG, such as temperature and humidity. And this mode is more effective for low-speed vehicles which cannot generate strong wind.

Although TENGs have great performance, PENGs contribute to transportation more early. In 2012, Lin et al. firstly utilized PENG by ZnO NWs to monitor transportation state [154]. The device was transparent owing to the transparent Indium Tin Oxides (ITO) electrode and the thin ZnO film (Fig. 9d). The device was robust enough to be compressed by vehicle tire, which delivered output of 10 V. On the other hand, it's also a process of monitoring. By placing two nanogenerators along the road with a certain distance (e.g. 0.6 m), the speed of vehicle could be calculated from the peak of signals (Fig. 9e). The vehicle speed from 1 to 4 m/s could lead to different time differences between two crests. Theoretically, the detection range is related to the sampling rate of the measurement system and the distance between the two nanogenerator devices. But the sample rate was 500 s^{-1} and distance was 0.6 m in this work, the detection limit was about 300 m/s, which is high enough. So this kind of device has wide speed monitoring application.

Intelligent development of highway is improved rapidly owing to its high use frequency. But self-powered technology by advanced nanogenerators dramatically reduces the human and construction cost. On the other hand, the sensors by nanogenerators with high sensitivity consumedly enhances the safety.

3.1.4. Tracks

Railway transportation is low-cost and rapid for a long trip. But trains have to run on the track. So tracks are the basic and matter a lot for railway transportation. It's a common sense that train has a high speed, and it's developed higher and higher in recent years [155,156], which brings intense vibration [113]. Vibration widely exists on the track, and usually brings damage to the track [157,158]. So it's a double benefit to harvest vibration energy for sensors. Li et al. proposed a wide band piezoelectric energy harvester using commercial PZT [159]. This work aims at expanding the working frequency limitation of cantilever beams. By adjusting the length of cantilever beam, it was demonstrated different length can change the optimum working frequency (Fig. 10a).

As a novel vibration energy harvester, using TENGs is ideal for track energy harvesting. Zhao et al. applied a typical contact-separate mode TENG as vibration accelerometer and energy harvester [160]. As can be seen in Fig. 10b, TENG was supported by springs. The authors stimulated and got the proper gap of 440 μm for effective contact of the two triboelectric materials. Then, they tested the performance of TENG. The result showed that the relationship between peak voltage and frequency was almost linear at acceleration of 1.25 m/s^2, which is the proof for TENGs as frequency sensors. What's more, there was a linear relationship between peak voltage and acceleration at frequency of 4 Hz and 6 Hz, which demonstrated TENGs as good acceleration sensors. The practical application of this work was to fix the TENG on the platform and charge lithium battery at 8 Hz and 1.25 m/s^2. After the process of 150 min, lithium battery was charged from 2.4 V to 3.0 V. Furthermore,

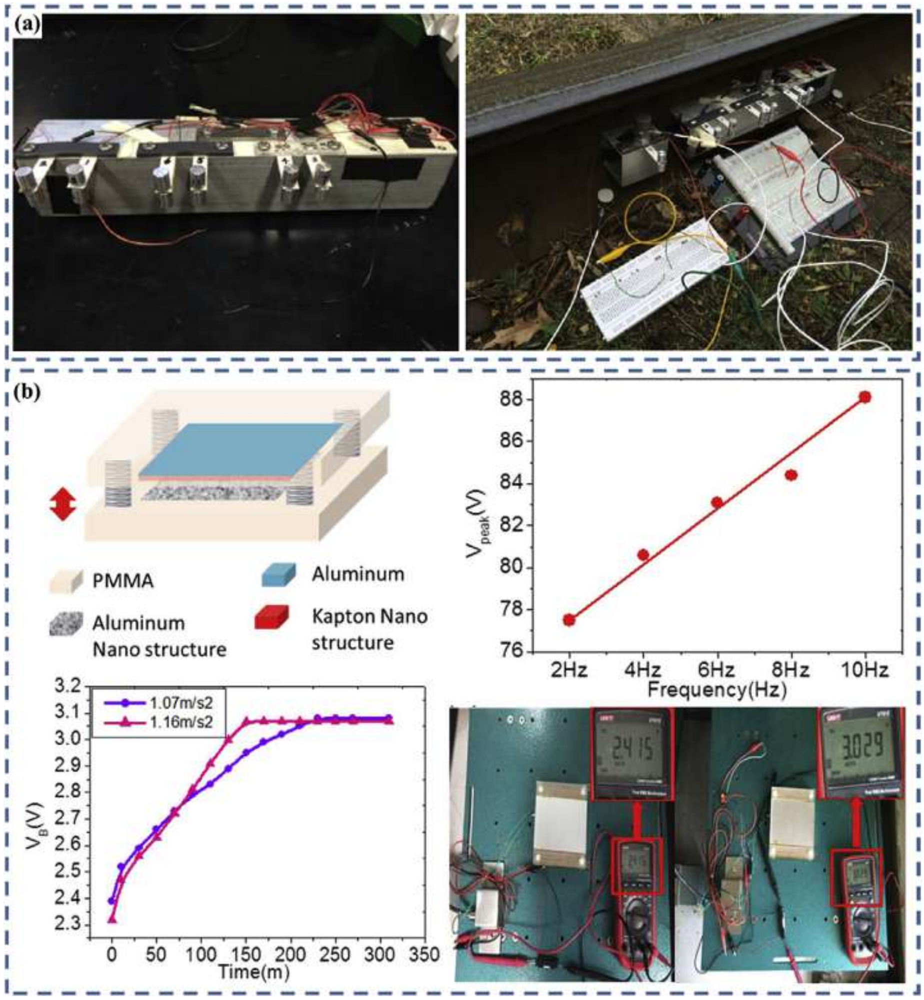

Fig. 10. Different methods for vibration energy harvesting of track. (a) Photograph of the device with different cantilever beam length for different frequencies vibration energy harvesting and the experiment test system [180].
(b) Typical contact-separate mode TENG by aluminum and Kapton for railway state health monitoring [160].

the lithium battery could power a wireless sensor to send data. And the data could be received. It's worth mentioning that this work is first for TENGs to monitor railway state health. It's the milestone to apply advanced nanogenerators on self-powered track monitoring. But regrettably, the TENG is not designed reasonably to match the special track structure.

Land roads constitute a large proportion in our daily travelling. Here, intelligent bridges are firstly introduced by combining with self-powered technology for real-time monitoring. Then, self-powered technology applied on the special tunnels as a significant step towards intelligent development is illustrated. In the next part, although intelligent highway is developed rapidly, nanogenerators can dramatically reduce cost. Finally, some studies about track intelligent development are referred, stating a truth that more investigation is needed to match the special track structure.

3.2. Water roads

Water roads need no building or maintain, leading to low-cost transport. But up to now, water roads are only a lane to many vessels. Because there's no gas station, rest area or even emergency place. The main reason is limited energy supply. However, water contains great energy, including tide, wave, and so on. What's more, compared with solar energy, water energy can be harvested anytime, regardless of dark. So how to make use of water energy becomes the key problem. Up to now, there are many studies based on it [161–165]. Ahmed et al. designed a duck-shaped TENG with free-standing rolling mode [166]. As depicted in Fig. 11a, free-standing Nylon balls acted as positive materials, while Kapton film with nano structure (enlarged view) acted as negative materials. When there was water wave, the duck shape made the device waggle. Therefore, the Nylon balls rolled and electricity could be generated.

For more efficiency, TENGs are usually combined with EMGs or multiple work modes. Wang et al. presented a fully-packaged ship-shaped nanogenerator as blue energy harvester [167]. Fig. 11b illustrates the detailed structure. The contact-separate mode TENG was driven by magnetic attraction. Because the cylinder with magnet could roll with water wave. The TENG of free-standing mode was similar with structure of Fig. 11a. But the movement was one dimensional owing to the cylinder structure, not balls. EMG part was a common structure of magnet and coil. The experimental result showed the TENG of contact-separate mode and the free-standing mode could deliver a maximum peak power of 850 μW and 165 μW, respectively. And the EMG had 9 mW. Benefiting from the multiple work modes, the device had great performance for seawater electrodialysis as self-desalination system. The desalination rate was demonstrated as 29.4% in 3 h and 98.5% in 24 h. It may help a lot for workers in emergency. After all, it's designed mainly for self-powered sensors. The position of destination on the sea is usually marked and searched when they want to get there. Self-powered position system can transmit signals proactively without

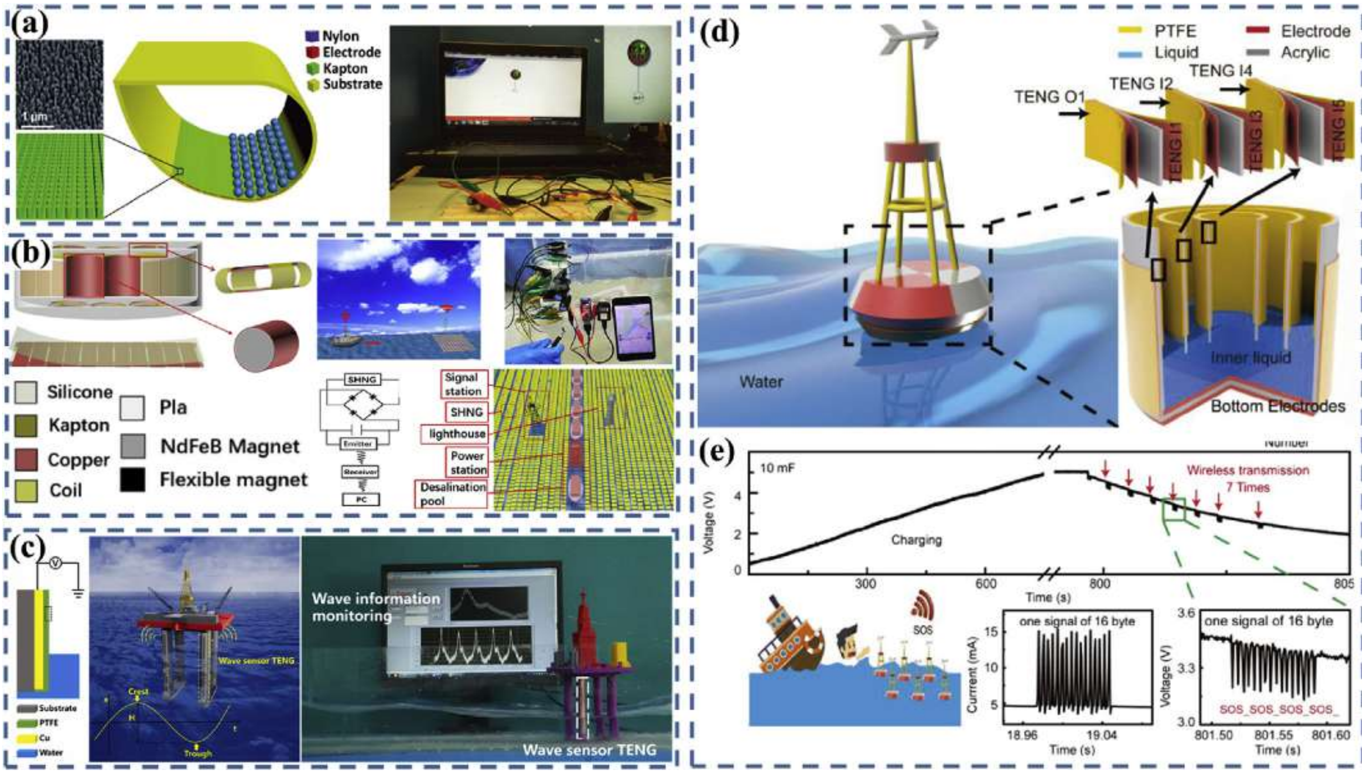

Fig. 11. TENG with different structure design for water wave energy harvesting and sensing. (a) Duck-shaped TENG with nanostructure modified Kapton for self-powered monitoring system [166].
(b) The device consisting of contact-separate mode TENG, free-standing TENG and EMG for self-powered position system applied on the sea and the further prospect of network TENG powering signal station, light house, desalination pool and so on as a rest area like highway [167].
(c) The liquid-solid interface TENG as a wave sensor applied on the sea [173].
(d) The multilayer-structure TENG applied on the water to harvest blue energy. (e) Illustration of wireless SOS system powered by harvested energy of TENG with a 10 mF capacitor [174].

external power source, which was demonstrated. And the corresponding circuit schematic is illustrated. For further prospect, a station can be set by plenty of nanogenerators, including signal station, light house, desalination pool and so on, just like the rest area of highway. What's more, it is self-powered, leading to improvement in intelligent water transportation.

Wave monitoring is key for marine equipment. In this regard, TENGs have good performance as active sensors. And many studies have demonstrated TENG works well at working mode of liquid-solid contact [168–172]. Xu et al. presented a highly-sensitive wave sensor based on liquid-solid interfacing TENG [173]. The schematic diagram could be seen in Fig. 11c. PTFE film acted as negative material while water, the common liquid, acted as positive material. Another work explored the liquid-solid interface contact electrification of TENG detailedly [174]. According to Fig. 11 d, the device had a multilayer structure, leading to a higher power density. And it could generate electricity no matter how it moved, such as moving up and down, shaking or rotation. But it showed that up and down movement had a higher output. To prove the advantage of liquid-solid mode, two kinds of TENG was compared. The result fully demonstrated that the output energy per cycle of liquid-solid TENG was almost twice as high as solid-solid TENG by calculation. The reason could also be concluded as contact surface. The solid-solid interface had more space than liquid-solid interface, because of the character of liquid. Another important element which can affect the output is surface hydrophobicity of PTFE film. TENG had the highest output in current, voltage and charge when the surface was super hydrophobic in this work. Finally, the authors used 18 TENGs as a network to charge a capacitor of 10 mF from 0 to 5 V within only about 13 min, according to Fig. 11e. And when connecting with wireless SOS system, the voltage started to reduce. Because wireless sensor started to work by consuming power and more when emitting. This is a very important application, because the self-powered technology has potential for emergency [175–177].

Water roads are important transportation for people and military, but the base station for rest and emergency like rest areas in highway needs further construction, which is the basic for intelligent development. The rapid development of blue energy brings possibility to harvest large energy. One day, we believe the self-powered unmanned station can help people have rest or even save their lives in emergency.

4. Summary and perspective

In summary, we have reviewed the progress of nanogenerators for ITS. On one hand, nanogenerators can harvest vibration, rotation and wind energy for electronics as power source. On the other hand, they are highly sensitive sensors. When combined with vehicles, nanogenerators with portability and high efficiency are fully demonstrated as power source to improve components to be self-powered and monitored in real time. Particularly, TENGs have external exhaust filtration function and good performance of anti-corrosion owing to the intrinsic electrostatic charge. As support of vehicles with safety, intelligent roads may be built with fewer cost when applied with nanogenerators. What's more, the self-powered technology by nanogenerators indeed promotes the intelligent development of special roads, such as bridges and tunnels. Since the idea of TENG for blue energy harvesting was proposed in 2014 [178], TENG has a rapid development in water wave energy harvesting owing to its operability in irregular environment and low frequency. Based on the vast ocean, there is a great chance to build an unmanned station on the ocean to provide emergency help or supply, like the rest area on highway.

Although nanogenerators indeed promote the intelligent development of transportation system, certain challenges remain. (i) The development of nanogenerators applied with some vehicle components in special environments is experiencing a bottleneck because of the limited performance of nanogenerators in extreme environment. For example, traditional TENGs are affected seriously with increasing humidity, limiting the development in water transport vehicles and water roads. Similarly, the condition of high temperature and high pressure in turbine blade mainly hinders real-time monitoring technology. Hence, functional nanogenerators need to be developed further for special environment demand, such as hydrophobic-treatment TENG and high-temperature PENG. (ii) More device structures need to be designed to match the special structures and work conditions of vehicles and roads. For example, all-metal train wheels are still not monitored in real time. The main reason is the all-metal structure and special fast work speed in tracks. So, it's an important research orientation to explore more useful device structures. (iii) The key stumbling block to commercialization for nanogenerators is power management and energy storage. In detail, the existing commercial power management circuit chips can't match the output of advanced nanogenerators well, especially the TENG's characteristic of high voltage and low current. On the other hand, it may reduce the life of commercial batteries or supercapacitors by charging and discharging at high frequency, which is common in airplanes and trains. Therefore, investigation with electronic and engineering field is needed to solve this problem.

In brief, the nanogenerator is a new developing field, but has enormous potential in ITS. With studies in this review, it is expected that nanogenerators can bring revolutionary development to ITS, resulting in more safety, more efficiency and more convenience for national defense and human's daily life.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

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Long Jin received his B.E. in Materials Science and Engineering from Southwest Jiaotong University (2015). He is currently pursuing Ph.D. degree in Materials Science and Engineering at Southwest Jiaotong University under the guidance of Professor Weiqing Yang. His research interests are nanogenerator and nanosensors for self-powered system.

Binbin Zhang received his B.E. from Southwest Jiaotong University in 2015. He is currently pursuing a Ph.D. degree in materials science and engineering at Southwest Jiaotong University under the guidance of Professor Weiqing Yang.

Lei Zhang received her B.E. degree in polymer material engineering from Chongqing University of Arts and Science in 2014. He is a graduate student in materials science and engineering at Southwest Jiaotong University under the guidance of Professor Weiqing Yang. His research focuses on the triboelectric nanogenerator and supercapacitor.

Weiqing Yang received his M.S. in Physics in 2007, and Ph.D. in Materials Science and Engineering from Sichuan University in 2011. He was a post-doctorate research fellow at University of Electronic Science and Technology of China from 2011 to 2013. Subsequently, he was a post-doctorate research fellow at Georgia Institute of Technology from 2013 to 2014, under the supervision of Prof. Zhong Lin Wang. Now he is a professor at South Jiaotong University and his research focuses on nano energy materials and micro/nano devices.