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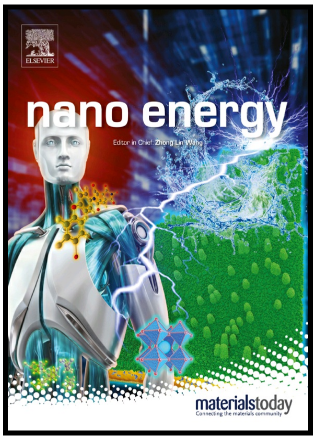

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Triboelectric Nanogenerator Based Self-powered Sensor for Artificial Intelligence

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Abstract

Triboelectric nanogenerator based sensor has excellent material compatibility, low cost, and flexibility, which is a unique candidate technology for artificial intelligence. Triboelectric nanogenerators effectively provide critical infrastructure for new generation of sensing systems that collect information by large amounts of self-powered sensors. This review mainly discusses capability and prospect of triboelectric nanogenerators being applied to intelligent sports, security, touch control, and document management systems. The above fields have paid increasing attention in artificial intelligence technologies, such as machine learning, big data processing and cloud computing, demanding huge amount of sensors and complicated sensors network.

Keywords:

Triboelectric Nanogenerator; Self-powered sensor; Artificial intelligence; Machine learning; Internet of things

1. Introduction

Nanogenerator (NG) can convert mechanical energy in the environment into electric power/signal effectively, including piezoelectric nanogenerator (PENG) [1] and triboelectric nanogenerator (TENG) [2]. NGs have novel advantages in harvesting environmental energy [3], and sensing signal at the same time. The self-powered sensor based on TENG/PENG has advantages of low power consumption, high sensitivity, high stability, and low cost [4]. TENG/PENG has good mechanical flexibility and environmental adaptability, and can be integrated into wearable electronic devices [5-8]. TENG/PENG based self-powered sensor was not only be used for harvesting mechanical energy in the environment, such as rotational motion [9], inertial motion [10] and vibration [11, 12], but also for detecting the concentration of gas such as hydrogen sulfide (H_2S) [13-15], monitoring the stress changes [16], and monitoring human vital signs signals (such as heart rate [17], pulse [18, 19], etc.). TENG/PENG shows ubiquitous application potential in the medical treatment and healthcare fields.

A general architecture of intelligent system consists of three layers: data collection layer, data communication layer, and data processing and analysis layer. A large number of sensor nodes of IOT act as data collection layer. Wireless networks are typical data communication layers. Cloud platform is used to data processing and analysis [20]. AI technology is the core of cloud platform. According to the amount of information required by AI algorithms, there are three AI algorithm application ways of sensor: first, the most natural application of AI is applied to data analytics for sensor data; second, a large number of sensor can be data source for AI, and new types of sensors maybe design for the requirements of AI, for example, AI sensors [21]; third, the new methods of AI are developed for the requirements of self-powered sensors, particularly TENG based self-powered sensors [22], as shown in Fig. 1. In addition, AI technology can improve the accuracy of information and recover incomplete information by learning the characteristics of complete information [23, 24].

In the future, there will be more than 30 billion sensors connected to the Internet of Things [25]. A wireless battery-free body sensor based on near-field communication has the power consumption of 4 mW [26]. The power consumption of the 30 billion NFC sensors reach up to 120 million watts, which is equivalent to burning about 15 tons of standard coal per hour (according to the United Nations standard of 1 kilogram of coal with a calorific value of 6880 Kcal). The power generation of the Three Gorges Power Station is 111.8 billion kWh in 2020. The power consumption of the sensors network is equivalent to 34 above power stations. Traditional sensors are powered by the grid and batteries, which will face large challenge while IOT want very large number of sensors for intelligent society in the future. Traditional sensors power consumption needs to be reduced by even several orders of magnitude. The self-powered sensor is good candidate for the power consumption problem [27].

Aside from the power consumption, the costs of installation and maintenance will increase significantly for very large number of sensors. TENG based self-powered sensors can overcome the limitation, which have unique advantages: high performance, simple structure, and low cost materials [28, 29]. Thus, TENG based self-powered sensors can provide practical solutions for massive and multi-dimensional sensors for IOT, which is the foundation of intelligence and provide data source for AI.

TENG/PENG will meet the energy supply and cost challenge of "smart dust", which mean a tremendous amount sensors constructing a distributed and mobile sensor network [30]. Traditional sensor systems usually need grid or battery. Sensor acts as a key role for the Internet of Things (IoT) [31]. For artificial intelligence application, large-scale installment of sensors will be a great challenge. Big data and artificial intelligence (AI) technology applications demand low cost "smart dust". TENG can be realized with a lot of low cost and flexible materials. Therefore, TENG is regarded as the most accessible due to simple structure and maintenance for big data and artificial intelligence.

Machine learning (ML) [32] technology is a widely used AI technology in data processing. The frontiers of ML is deep learning [33], which can be used to classify and process large amount of sensor data. Typically, large-scale deep learning systems require data of 1 million or more because AI technology is inseparable from a large amount of data for training [34]. Take a smart cities as example, millions sensors are needed to obtain such large amount of data, and a sensor node costs about 10 USD [35]. Thus, such a large scale sensors system costs tens of millions to hundreds of millions USD, as well as the cost of energy and maintenance for the nodes. TENG-based self-powered sensor arrays can be used for scalable fabrication，so it can be made at extremely low cost [36]. Jeon et al. proposed [37] a wearable fabric touchpad based on TENG which costs about 0.4 USD. Some TENG sensors can be used in harsh environments to reduce maintenance costs [38, 39]. Therefore, the TENG sensor is very suitable as a sensor for machine learning data supply, leading to new impetus for the development of AI technology. The ML method is an algorithm that can mimic human cognitive processes. It can learn rules from data and automatically improve the learning process without explicit programming.

The ML technology can also optimize the sensor network and monitor the dynamic environment that changes with time [40]. The machine learning based on artificial neural networks (ANN) can also compress and restore data for IoT and edge computing systems, thereby improving the transmission efficiency for sensor data collection and processing [20, 41]. Especially, the machine algorithms can retrieve the real environmental parameters through incomplete data information, such as using intelligent algorithm to trace the gas environment according to the traceability of gas [42].

TENG based ML technology can be a realistic approach for intelligent security identification, intelligent sports [43], human behavior analysis [44], gas analysis [45], gas sensor drift processing [46], transportation [47] and document management [48]. These data-driven application scenarios often require large-scale and large-area deployment of sensors, and long-term monitoring for days, weeks, or even months. The intelligent algorithms process large-scale sensor data efficiently, and enable the effective information extraction.

2. TENGs for Intelligent Sports

TENG based self-powered sensor effectively obtain movement signals from body movement as wearable sensors, which can be used for training and competition of athletes, physical rehabilitation, and personal fitness [49-51]. TENG based self-powered sensor had been used for competition field sensors to collect training and competition data [43]. Intelligent sports will demand very large number of sensor nodes due to personal fitness. Typical limb motion sensor has the total power consumption of 450mW and the continuous working time of 3.5 hours [52]. Thus, there is power consumption problem for traditional sensors based intelligent sports. TENG sensors can provide multi-dimensional data for the AI algorithm, and very large number of self-powered sensor nodes provide a good solution for power consumption problem.

TENGs based self-powered pressure/touch sensors are made from a variety of materials, which can be used in sports training and competition venues or equipment to collect training and competition data. Recently, Luo et al. designed a flexible wood-based triboelectric nanogenerator (W-TENG) as a self-powered pressure sensor in 2019 [43]. The wood will be more flexible after chemical treatment and hot-pressing. The treated wood is used as the triboelectric material of W-TENG. The single-electrode mode W-TENG made of this material is lighter and thinner, which can be used to make a smart ping-pong table for training and sport data analysis systems, as shown in Fig. 2a.

The smart ping-pong table detection system can achieve several advantages: Firstly, the W-TENG array is based wood and installed on the desktop, so this design provide similar materials so do not affect the function of ping-pong table; Secondly, the impact points of ping-pong ball are accurately identified, and the sensor data is analyzed with big data through statistics of the drop point distribution data; Thirdly, the analysis results can guide the athletes' training， which may be used to identify their sports style; Finally, it can provide judgement evidence for the referee in the game by data from the controversial edge ball. Fig. 2b shows the entire process from the ping-pong ball hitting the table to the input sensor signal. The whole system uses self-powered wood-based triboelectric sensor (W-TES) to obtain information of the velocity and direction of ping-pong balls. Fig. 2c shows the self-powered ping-pong ball drop point distribution statistical system and the distribution of statistics of the drop points during the experiment. Fig. 2d shows the voltage output of ping-pong ball as it hits the table at different velocity. The velocity and output voltage are positively correlated. According to this property, the relationship between velocity and sensor output voltage can be established for the measurement of ball velocity. Fig. 2e shows the trajectory of a ping-pong ball on a 4×2 pixelated W-TES array. The output voltage signal of each channel in the array changes with time can be used to track the trajectory of the ping-pong ball.

The W-TES can collect information of the drop point, velocity and other data of the ping-pong ball, and big data analysis of these data can help guide their training and develop better competitive strategies. These data can be used as the corresponding sports characteristics of each athlete. Moreover, the above data can also be used to design intelligent robots to enhance athlete training and provide data support for the development of artificial intelligence. Similar to the smart table tennis table, such self-powered sensors can also be applied to other ball sports scenarios. For example, W-TES can be used for volleyball or basketball helping determine whether the ball is out of bounds. Compared with traditional camera-based motion analysis system, the sports monitoring system based on TENGs can improve the accuracy of sensing and eliminate the interference of human factors.

Foot activity is one of the main sources of kinetic energy for human movement. Zhang et al. designed a smart socks for harvesting energy from the body to transmit wireless gait sensory information (Fig. 2f) [49]. Gait sensory data enter the preprocessing circuit and MCU to obtain an analog signal. Then the signal is sent wirelessly to the PC for identification by 1D CNN. The CNN can divide gait into 5 types: leaping, running, sliding, jumping, and walking. The trained 1D CNN has a classification accuracy of 96.67% for the 5 gait types. As the artificial intelligence, deep learning extracted advanced features to identify gait actions in this case, which is important part of the personal fitness monitoring system.

Wen et al. proposed a CNN-based TENG sensor glove for the recognition of baseball throwing gestures [50]. As shown in the Fig. 2g, collect and collect through gloves installed with TENG sensor gesture data. The CNN analyzed these electrical signals, then get the gestures of throwing the ball, which include palm ball, curved ball and knuckle ball. The trained CNN can get a high gestures recognition accuracy 99.167%. Virtual sports can collect athlete motion data through sensors, such as athletes' pitching gestures, to simulate real game.

Self-powered sensor will be a new direction for the development of future IoT sensor networks. The original intention of IoT is to realize the interconnection between people and things and between things. Self-powered sensors will be sensitive, convenient and send back a large amount of data in real time. Sensors data reflect changes in the real world, so they need to be evaluated thoroughly and carefully. This requires intelligent technologies such as cloud computing and artificial intelligence to process data. In addition, the combination of intelligent data processing and self-powered sensors is a new era for the IoT.

3. TENG based Artificial Sensory Nervous System

Artificial sensory nervous system can process information like the biological sensory nervous system [53-55]. Chen et al. proposed a self-powered bionic tactile peripheral (TPNS) tactile sensor based on tribotronic transistors [55], as shown in Fig. 3a. The nervous system is less than 15 nW in the inactive state and 28.6 mW in the active state. Thus, power consumption also is a challenge for artificial sensory receptors based on traditional electronics, while the number of tactile sensors increase [53-55]. Hundreds of millions of inactive nervous systems consume a few watts of energy, which is energy problem of traditional sensors [55, 56]. The self-powered nervous system sensor based on TENG directly convert external energy stimulation into electrical signals without electric power supply.

Liu et al. proposed an artificial sensory memory, which uses triboelectric sensory receptors (TESR) to drive integrated field effect synaptic transistors (FEST) under different external pressures, as shown in Fig. 3b [56]. The devices can be used for real-time neuromorphic computing. Liu et al. coupled an electric-double-layer organic field effect transistor (EDLT) and a TENG to obtain a self-powered synapse transistor (SPST) [57]. External contact can drive SPST to spontaneously generate electrical signals, realizing self-powered tactile signal sensing. Fig. 3c shows the biological synapse structure and the corresponding SPST equivalent device. It can be seen from the figure that the voltage signal generated when two TENGs work simultaneously is equivalent to the voltage signal generated when each TENG works individually. This transistor well simulates the independent characteristics of the inputs of biological neurons, and also has nonvolatile memory and long-term plasticity. In addition to tactile neuromorphic circuits, Liu et al. also proposed a TENG based artificial auditory pathway for self-powered acoustic sensor, as shown in Fig. 3d [58]. Electrical signals converted from external sound signals are generated by TENG. An acoustic synapse does signal conversion and neuromorphic calculation. It can be considered as artificial intelligence of acoustic signal recognition and sound azimuth detection.

4. TENGs for Intelligent Signal Recognition

TENG based self-powered touch sensor is an active sensor, which can used for human-computer interaction [59]. The touch sensor acquires information on the trajectory, texture and shape of the object through contact with the object [59-61]. AI process and analyze the data from touch sensor, which provides touch track recognition and tactile mapping.

The TENG-based pressure/touch sensor was used to design human-machine interface (HMI) [37, 62] for signal recognition by the deep learning. Yun et al. [62] used TENG as a touch sensor to make self-powered triboelectricity-based touchpads (TTP), which consisted of a 7×7 (49 pixel) TENG sensor array with polyethylene terephthalate (PET) as the substrate, fluorinated ethylene propylene (FEP) as the electrification layer, indium tin oxide (ITO) as the electrode. The number "2" is handwritten on the TTP, as shown in Fig. 4a. The flexibility of device was tested by bending TTP, and its excellent flexibility was observed (Fig. 4b). As shown in Fig. 4c, using reactive ion etching (RIE) can increase the effective contact surface between the contact position and non-contact position, resulting in more surface electrification and further improvement in the detection sensitivity of device, and at least an increase of 1.54 V and 12.34 nA in its output. As shown in Fig. 4d, The TTP has two working modes: vertical tapping and sliding mode. Then, the charge distribution during the surface charge transfer process was simulated by COMSOL. TTP can generate electrical signals based on the movement of the external object without any external power supply. Fig. 4e shows the binarized signals generated by each unit when the handwritten digit "2" was written. The detection position deduced from the signal mode corresponds to the actual pixel being touched. Writing the natural numbers from "0" to "9" on the touchpad respectively, the identified digital lattice effect is shown in Fig. 4f. Fig. 4g shows the process of the whole system from signal acquisition to output recognition.

Handwritten signal input to convolutional neural network (CNN). CNN is composed of three layers: input layer provides input for neurons; the hidden layer includes a convolutional layer (Conv); and the output layer. The classical back propagation algorithm and the modified national institute of standards and technology (MNIST) database as training set were used for the training. After experiments on TTP at bending angles of 0°, 119° and 165°, the accuracy of output signal recognized by the deep learning network is still up to 93.6%, 92.2% and 91.8%. This flexible self-powered TTP can provide a new way of human-machine interaction and signal recognition by attaching to the human body or other surfaces.

5. TENGs for Intelligent Security System

TENG based self-powered sensors act as data source of keystrokes and handwriting habits for AI, which can be used for user identification by distinguishing the behavior of users [63-65]. TENG sensor can obtain comprehensive handwriting information including position, velocity, acceleration, pressure, force, direction, and pen inclination during writing [65]. Multi-dimensional information can improve the accuracy of user input recognition and also improve system security.

The keyboard is a common device for human-computer interaction. Each person have different typing habits. Self-powered pressure sensor based on TENG/PENG can collect these signals. ML algorithm distinguish the features of typing habits. A keyboard based on TENG/PENG self-powered pressure sensor was developed [63, 66, 67]. The signals generated by the user's typing on the keyboard input to the ML algorithm for determining the user identity. This is a solution for the future intelligent security system.

TENG can be integrated with the electromagnetic generator (EMG) as a brand-new combination to collect environmental mechanical energy and provide energy for microelectronic devices [66]. The output characteristic of TENG is designed for detecting signals of force and pressure [66]. According to the characteristics of voltage signal and current signal, this hybrid self-powered sensor can accurately record the typing behaviors of typists, such as pressing force, typing velocity and typing frequency. And then quickly analyze these data by using intelligent technology such as ML method. From the different typing habits of each person, the typing characteristics can be obtained after ML analysis. Identifying the current typist by typing characteristics can be used as a solution of system security. The hybrid active sensor multilayer structure and the typing signal obtained by electromagnetic-triboelectric active sensor (ETAS) is shown in Fig. 5a. In the process of pressing ETAS, the voltage signal of TENG part and the current signal of EMG part are recorded in real time through the data acquisition system. Through the combination of TENG and EMG, a new solution is provided for safety equipment based on the human-computer interaction.

Support vector machine (SVM) algorithm was used to process the electrical signal output from self-powered sensor based keypad [63]. Fig. 5b shows the brief process of training and recognition for the SVM-based security system. In addition, a numeric keypad was constructed in this work, consisting of 16 triboelectric keypads that are stretchable and conform to a circular surface (Fig. 5c). This one-stop hardware and software integrated security system can conduct authentication through unique typing behavior on the terminal, and the system can accurately identify users with an accuracy of 98.7%. The proposed system consists of two main processes, the training process and the authentication/identification process. During the training process, the user will enter a string by pressing the button on the device, and then get the induced electrical signal. The predefined features are then extracted from the collected signals and used to build the feature database. During the authentication/identity process, the test document is built in the same steps and cross-referenced with the existing document database to determine whether the test object is an authorized user (authentication) or who the test object is (identity). The core of the identity recognition system is a SVM-based software platform, which is integrated with the triboelectric numeric keypad to build a two-factor authentication/recognition system (Fig. 5d). The keystroke features are then extracted using specific signal processing techniques. As shown in Fig. 5e, M in the figure represents signal magnitudes, L represents typing latencies, and H represents hold time. Given an exemplary sequence of six numbers, the algorithm can extract 17 features from it. After five users input the number sequence for 150 times in total, the radar map of the normalized feature mean of the five users can be obtained, from which the different typing behavior characteristics of each user can be clearly seen. During the training, these normalized feature vectors are then used to build user profile models through supervised learning with the help of principle component analysis (PCA) and SVM. To implement authentication and identification, the difference scores between input from the same user and input from different users are plotted in Fig. 5f. The diagonal part represents the input difference between the user and himself. It can be clearly seen in the figure that the score on the diagonal is much lower (more blue). Therefore, the input difference from the same user is much less than other users.

Zhang et al. proposed a TENG based self-powered handwriting pad for AI security system, which can distinguishes the characteristics of individual handwriting habits [65]. SVM-based decision tree (SVMDT) method is used to analyze these personal handwriting and identify the writer of the handwriting, as shown in Fig. 5g.

Through TENG-based pressure sensor, electrical signals are obtained, and typing characteristics of users are obtained through ML analysis, and the user's identity is verified. Traditional fingerprint recognition and face recognition have can be easily copied. Identifying users by their typing habits hardly replicate, so the method improve system security.

6. TENGs for Intelligent Document Management System

Intelligence document management system with large number of sensors is one of the widely used fields of intelligence. For example, the Library of Congress is the largest library in the world with more than 170 million items. The radio frequency identification (RFID) technology is used for book managements, which can read the information and status of the document. While a large number of documents are not in the library or need real-time monitoring, RFID also has power consumption problem, because RFID devices is actually powered by a card reader. A low-power RFID receiving antenna power consumption is 0.25mW [68]. ICODE SLIX SL2S2002_SL2S2102 is a typical commercial intelligent RFID label that can be used in libraries, and its minimum input power is 40 μW. Thus, TENG based self-powered sensors can be used in conjunction with books or documents due to the readability, flexibility and lightweight of the paper [48]. It can actively process the signals generated by human movement, obtain book movement information, and user interaction information with the book.

Zhang et al. proposed a Transparent paper-based TENG as a self-powered paper book anti-theft sensor [69]. As shown in the Fig. 6a, one-grating-structures and multi-grating-structures are located on both sides of the paper. The electricity generated by reading the book can record the reading information of the document and trigger the warning buzzer.

He et al. proposed a thin, flexible and sustainable self-powered sensor by a paper-based hybrid nanogenerator for books or documents management [48]. A wireless induction system circuit has been developed by integrating single-electrode paper TENG with signal processing module, as shown in Fig. 6b. The working mechanism of the single electrode through paper/finger touch is shown in Fig. 6c. In Fig. 6d, paper-based calculator is made of 16 separate square TENGs as function keypads. The sensor in Fig. 6f can be made into a thin on-paper sensor for reader and book interaction.

Paper and fingers have higher triboelectric properties than FEP [70, 71]. This type of sensor can capture data from human activity information such as flipping pages and moving books/documents, and real-time analysis of these book data can facilitate book management. By analyzing some specific data, such as how often a book is moved and where more popular books are located, can help with library management and planning. The on-paper sensor can also send back reading information to the data analysis, providing customized services for readers. This also provides ideas for other areas of multi-data management, such as paper document management.

7. Artificial Intelligence Technology Enhanced Self-powered Sensors

The output voltage of TENG/PENG can be used to measure the amplitude and frequency of applied stress. Thus, TENG/PENG can be used as the pressure/touch sensor for pressure detection, tactile imaging [72], touch screen, safety inspection, health inspection, and electronic skin [73]. Stretchable and deformable TENG can be placed on the surface of human skin to monitor the physiological activities of human body, such as joint bending, extension and body rotation [44, 74, 75]. The real-time signal of high sensitivity TENG is very important for medical detection and disease diagnosis. Furthermore, the TENG based sensors can be used for gesture recognition [76]. The combination of self-powered motion sensor and data processing system based on ML can realize the sign language recognition of people with language impairment.

Zhou et al. [77] demonstrated the feasibility of using stretchable sensor to realize sign language recognition. The PCA algorithm is used for feature extraction, and the SVM algorithm for gesture recognition. The recognition accuracy is 98.63% with recognition time less than 1s. TENG based self-powered sensor system can improve above system, which may help disabled people to live and communicate normally. Self-powered sensors can also collect the weak mechanical energy generated in other physiological activities of human body, such as heartbeat, breathing and voice [78-81]. The data processing technology may help to monitor human health [82]. Voice can be recognized by vocal cord vibration, which can be made into a biosensor attached to the skin of the throat. Voice print recognition and speech recognition can be realized by combining with data processing technology [83].

Because TENG-based self-powered sensors are mostly flexible and highly sensitive, they can be used for real-time collection of critical body data of athletes with minimal impact on their normal training [43]. We can then use intelligent analysis technology to quickly analyze and detect the large amount of data collected to reconstruct muscle movement and accurately analyze exercise habits. For example, the movements of athletes can be detected and identified in real time using AI classification techniques [84] .

The TENG-based sensor is easier to deploy and consumes less power than the traditional metal oxide semiconductor (MOS) gas sensor. A large number of self-powered sensors will generate massive transmission data. By big data and artificial intelligence analysis of the sensor data, AI technology can also enhance the sensor's capabilities and improve the efficiency of sensor utilization. For example, sensor drift will lead to distortion of gas information obtained by the gas sensor, which will greatly reduce the performance of back-end system for gas identification and gas concentration regression model [46]. There are usually two main reasons for sensor drift: (i) the gas sensor works for too long or is exposed to external pollution during operation, which leads to irreversible changes in the micro-structure such as the sensing film; (ii) changes in the external environment of gas sensor (such as temperature, humidity, etc.) and uncontrollable changes (such as transmission system noise). The sensor drift will bring huge maintenance costs and limit the large-scale application of gas sensors. Artificial electronic noses an important application of gas sensor [85], which need an effective way to overcome the influence of gas-sensitive drift.

In 2012, Vergara et al. collected data sets of six different volatile organic compounds in three years and achieved good results in dealing with the gas sensor drift [46], using by the ML method of classifier. Yan et al. used the maximum independent domain adaptation (MIDA) algorithm to transform the sensor drift problem into the discrete and continuous distribution change problem of feature space [86]. The ML methods provide the algorithm for gas sensor drift.

The ML methods, for example, deep learning also can improve the sensitivity to a certain kind of gases [45]. By enhancing the strength of these signals, the gas sensor can detect many kinds of gases at the same time, thus improving the utilization efficiency. Recently, smell sense devices based on electronic skin had been paid attention [14]. The selectivity is a challenge for such gas sensor [87]. The actual sensor usually responds to different gases. For different types of gases, the electrical signal or its trend generated by the gas sensor has certain characteristics. Deep learning may extract information about different gas components from the same sensor by using the feature extraction capability.

The self-powered gas sensor can be deployed quickly and easily to collect gas data from different spatial locations [42, 88-91]. Bilgera et al. proposed the use of Convolutional Long Short-Term Memory [92] Neural Networks (CNN-LSTM) to trace the source of outdoor gas [42]. As shown in Fig. 7a, the gas sensor was deployed as a 5×6 sensor matrix at an interval of 1.5 m, and the anemometer was placed in the center of entire matrix. During the test, the CNN-LSTM received sensor data and was able to locate the location of air source with a prediction accuracy of 93.9%. The gas source used in the experiment is located in one of the cells in the grid and releases ethanol vapor outward at a flow rate of 500 mL/min. Fig. 7b shows the structure of the CNN-LSTM. The network input is wind data collected by the gas sensor matrix (5×6) and anemometer. After the gas sensor matrix is input and processed by CNN, output feature vector is obtained. As the gas concentration in the sensing matrix and wind direction in the environment change with time, CNN feature vector and wind vector were taken as the input of LSTM. Then the LSTM layer predicted each time step. Finally, the whole sequence was combined as the input of DNN and the air source location information was finally output. As shown in Fig. 7c, it can be found that the highest predicted value is near the true value, which proves that the network has learned information about gas distribution. In the heat map in Fig. 7d, it is obvious that the network output overlaps with the real source, and the network can accurately predict the location of the air source. Moreover, the above sensors are traditional discrete sensors of a limited number, which can be replaced by a large number of independent removable self-powered gas sensors to obtain more information and reflect more accurate air source information.

Self-powered gas sensors also can be deployed in more complex and dangerous environments rich in external mechanical energy, such as urban pollution gas monitoring, volcanic gas research, and chemical gas research [38, 39, 93]. The data processing system may adopts the neural network model which can process a large amount of data. The location of gas leakage in the environment will be determined, reducing the adverse effects on human health. Accurate positioning of gas leakage can facilitate the elimination of risks, and it has a more promising prospect for the future application of gas traceability.

7. Challenges and Potential Application for Future Self-powered Sensor

In this review，the current cases of AI method used for data from TENG are reviewed, especially machine learning methods of AI. The future of intelligent society will be all about sensor technology and AI algorithms. The variety, low cost, high sensitivity, and flexibility of TENG sensors allow the collection of data from human bodies and environments, which can be used as a "smart dust" to carry out independent continuous work and generate massive data for processing. AI technology can help TENG achieve more functions and applications. TENG provides AI with the massive data and more dimensions of data to increase the prediction accuracy of the AI model.

Even though great progress for AI applications of the TENG has been made, there are still some challenges that need further develop in this research area:

(1) Further investigation in AI analyses TENG sensor data. This way is currently the most natural application of AI for TENG based sensors, which complement existing traditional and self-powered sensor system. Especially medical, sports, transportation and environmental fields are hot application areas of AI.

(2) Development of large-scale TENG sensors for AI. The amount of information required by AI algorithms demands many different type and very large number of sensors, which named as AI sensors. Traditional sensor systems have power consumption problem in this case. Self-powered sensor system based on current energy harvesting devices and conventional sensors needs to be reduced the costs by even several orders of magnitude. TENG based self-powered sensor systems have high performance, simple structure, and low cost materials.

(3) The new methods of AI need developed for TENG based self-powered sensors. Random characteristics of environmental energy is a general question for information for AI while large number of TENG based sensors act as data source. When the energy in the environment is insufficient, the data obtained by the TENG sensor is random and low accuracy. AI technology need recover incomplete information and improve the accuracy of information by learning the characteristics of complete information. The future of TENG based AI algorithms also develop AI technology, self-powered edge computing nodes, robotic sensory such as joint movement control [94], tactile system [95] and auditory system [96].

(4) Machine learning is a widely used AI technology in data processing, TENG based machine learning is suitable of high performance processing, high resolution, and high speed fields with small data and incomplete information from each self-powered sensor. This is very different from commercial and image processing, which has sufficient and complete data. In

other words, TENG needs a new ML design and training method. Energy management of networks based on TENG will be also a new research direction for AI applications of TENG [97]. ML is expected to be used for energy management for self-powered sensor system in the future.

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Figure captions

Fig. 1. Relationship between TENG and AI. Three AI algorithm application ways of sensor: i. AI support the data analysis of the TENG, which is the most natural application of AI for sensor data; ii, TENG acts as part of the data source for an AI system, which demand a large number of sensor, and new types of sensors need design for the requirements of AI; iii. the new methods of AI are developed for the requirements of self-powered sensors, particularly TENG based self-powered sensors.

Fig. 2. Application of TENG based sensor in intelligent sports (a) The structure of intelligent ping-pong table based on W-TENG. [43] (b) Operation procedure of statistical system of self-powered drop point distribution based on W-TENG. (c) The self-powered drop point distribution statistical system. (d) Sensor output voltage at different ball velocity. (e) Principle of W-TENG sensor array to analyze the trajectories and drop points of table tennis. (f) TENG sensor based smart socks for sports gait information recognition. [49] (g) CNN-based TENG sensor for sports gesture recognition. [50]

Fig. 3. Artificial circuits based on TENG simulate the biological sensory nervous system. (a) TENG based self-powered artificial tactile peripheral nervous system. [55] (b) Triboelectric receptors based Self-powered high-sensitivity tactile sensory memory. [56] (c) TENG based self-powered artificial synapse driven. [57] (d) TENG based self-powered artificial auditory pathway. [58]

Fig. 4 TENG based touchpad structure and working principle of handwriting recognition system. [62] (a) Schematic diagram of touchpad composition, write and draw the number "2" and the Touch screen after bending. (b) The transmission spectrum and absorption spectrum of the touch panel. (c) The scanning electron microscope (SEM) image of the surface of the device. Top image: before RIE treatment, bottom image: after RIE treatment. (d) The potential distribution of the triboelectric charge induced surface and electrode surface of the touchpad in different operating modes. (e) The trace on the touchpad of the handwritten number "2" and the output electrical signal generated by the touchpad. (f) The track of the numbers 0-9 on the touchpad. (g) Neural network structure and the process of recognizing handwritten digits on the touchpad by the trained neural network.

Fig. 5. Intelligent security system based on TENG based self-powered sensor. (a) The TENG-EMG hybrid active sensor multilayer structure and its output performance. [66] (b) The SVM-based triboelectric keypad security system training and recognition flowchart. [63] (c) 16-key stretchable keyboard. (d) Operation flow chart of system hardware. (e) The curve of the electrical signal and time generated by the user's typing, and the feature radar chart of the five user's typing. (f) A cross-user input difference score matrix with different feature type combinations. (g) TENG based handwriting self-powered recognition for machine learning user classification. [65]

Fig. 6. TENG based self-powered sensor for document management. (a) TENG based sensor for recording page turning and book anti-theft. [69] (b) Design schematic diagram of self-powered sensing system based on TENG. [48] (c) Finger touches the paper to trigger the working mechanism of single electrode TENG. (d) The paper-based triboelectric/piezoelectric hybrid nanogenerator (PHNG) sensor is used as a document management system and a paper-based calculator.

Fig.7. Data analytics for gas sensors by machine learning. [42] (a) The number in each unit corresponds to the position of the gas sensor. The gas source in each unit is slightly offset between the lower left corner of the sensor. (b) Simplified architecture of CNN-LSTM for gas traceability. (c) The output of the lowest prediction rate label of the DNN and CNN-LSTM. (d) The unit

position predicted by CNN-LSTM is consistent with the air source position.

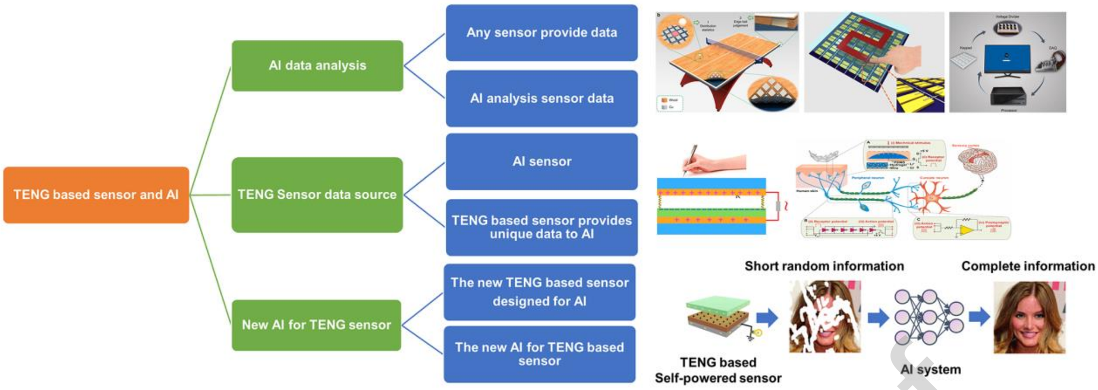


Fig. 1

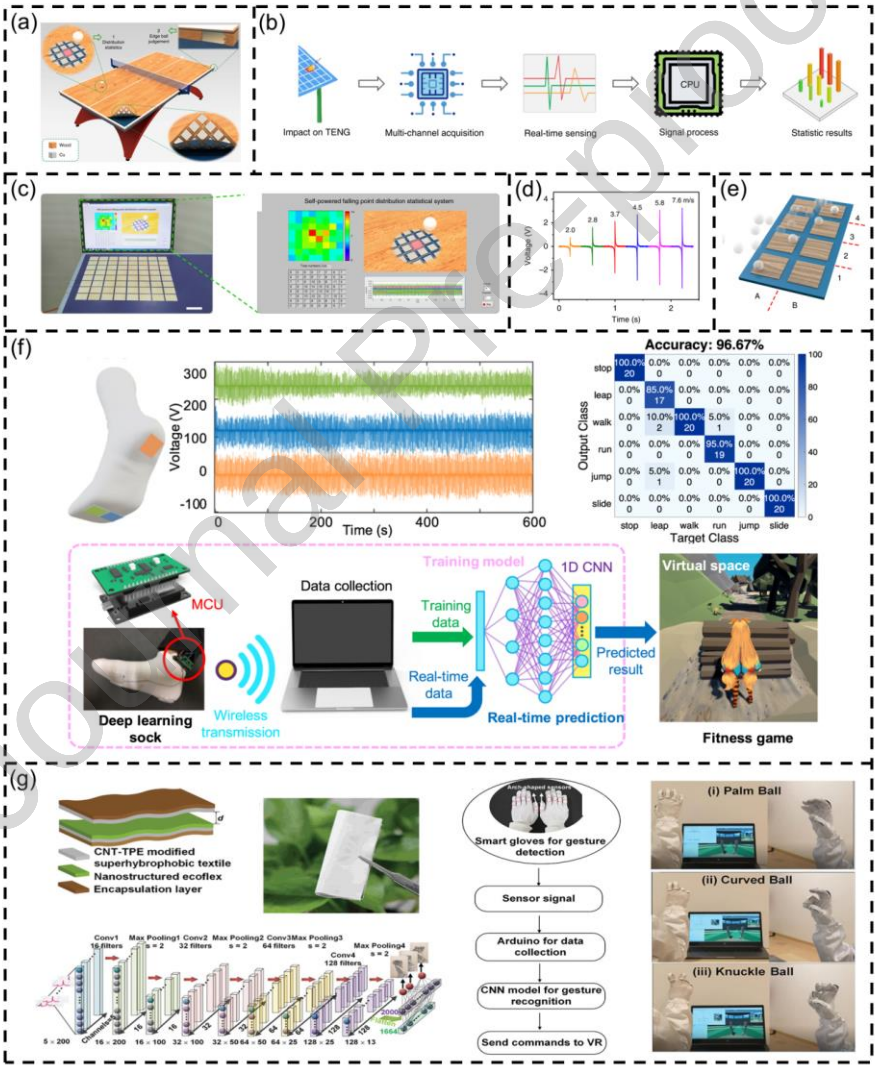
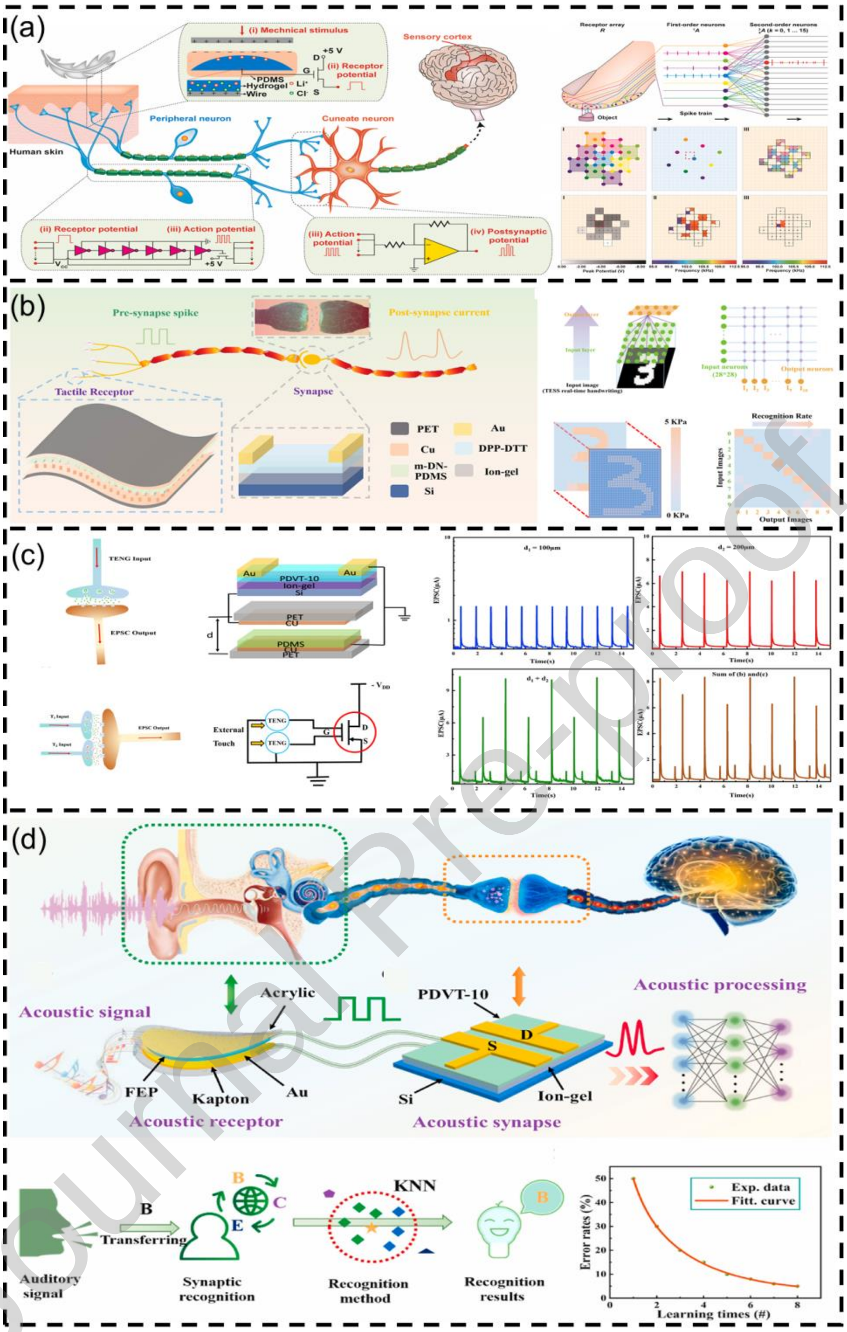


Fig. 2


(a)
(i) Mechnical stimulus
+5 V
D
G
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(ii) Receptor potential
PDMS
Hydrogel
Wire
Li+
Cl-
Sensory cortex
Human skin
Peripheral neuron
Cuneate neuron
(ii) Receptor potential
(iii) Action potential
Vcc
+5 V
(iii) Action potential
(iv) Postsynaptic potential
Receptor array
First-order neurons
Second-order neurons
Object
Spike train
(b)
Pre-synapse spike
Post-synapse current
Tactile Receptor
Synapse
PET
Au
Cu
DPP-DTT
m-DN-PDMS
Ion-gel
Si
Input image
(TESS real-time handwriting)
Input neurons (28*28)
Output neurons
5 KPa
0 KPa
Recognition Rate
Input Images
Output Images
(c)
TENG Input
EPSC Output
Au
Au
PDVT-10
Ion-gel
Si
PET
CU
d
PDMS
CU
PET
External Touch
TENG
TENG
G
D
S
- VDD
d1 = 100μm
d2 = 200μm
d1 + d2
Sum of (b) and(c)
EPSC(μA)
Time(s)
(d)
Acoustic signal
Acrylic
PDVT-10
Acoustic processing
FEP
Kapton
Au
Acoustic receptor
S
D
Si
Ion-gel
Acoustic synapse
B
Transferring
Auditory signal
B
C
E
Synaptic recognition
KNN
Recognition method
B
Recognition results
Exp. data
Fitt. curve
Error rates (%)
Learning times (#)

Fig. 3

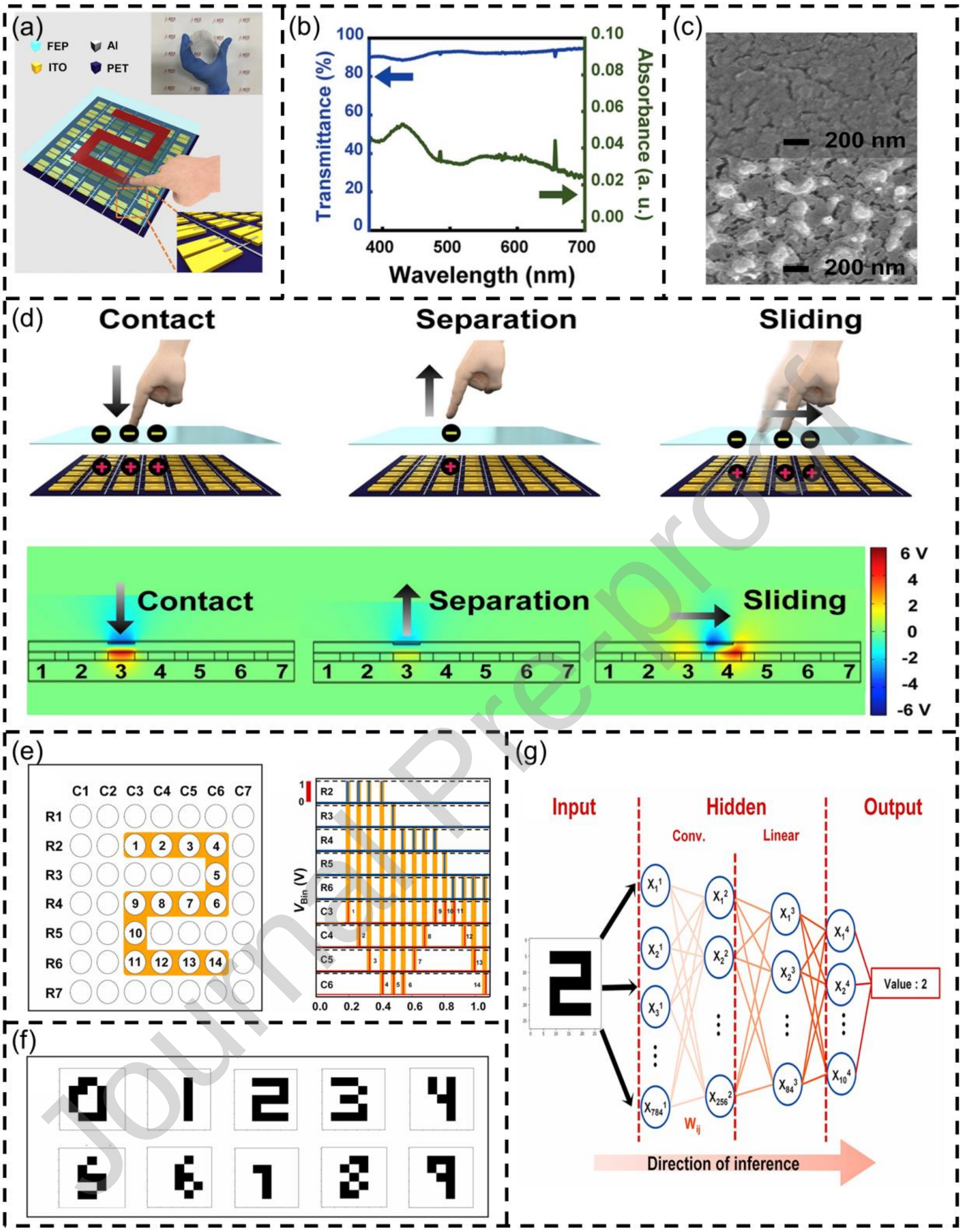

(a)
FEP
Al
ITO
PET
(b)
Transmittance (%)
Absorbance (a. u.)
Wavelength (nm)
100
80
60
40
20
0
0.10
0.08
0.06
0.04
0.02
0.00
400
500
600
700
(c)
200 nm
200 nm
(d)
Contact
Separation
Sliding
1 2 3 4 5 6 7
6 V
4
2
0
-2
-4
-6 V
(e)
C1 C2 C3 C4 C5 C6 C7
R1
R2
R3
R4
R5
R6
R7
1 2 3 4 5 6 7 8 9 10 11 12 13 14
V_{Bin} (V)
R2
R3
R4
R5
R6
C3
C4
C5
C6
0.0
0.2
0.4
0.6
0.8
1.0
(f)
(g)
Input
Hidden
Output
Conv.
Linear
X_1^1
X_2^1
X_3^1
X_{784}^1
X_1^2
X_2^2
X_{256}^2
X_1^3
X_2^3
X_{84}^3
X_1^4
X_2^4
X_{10}^4
W_{ij}
Value : 2
Direction of inference

Fig. 4

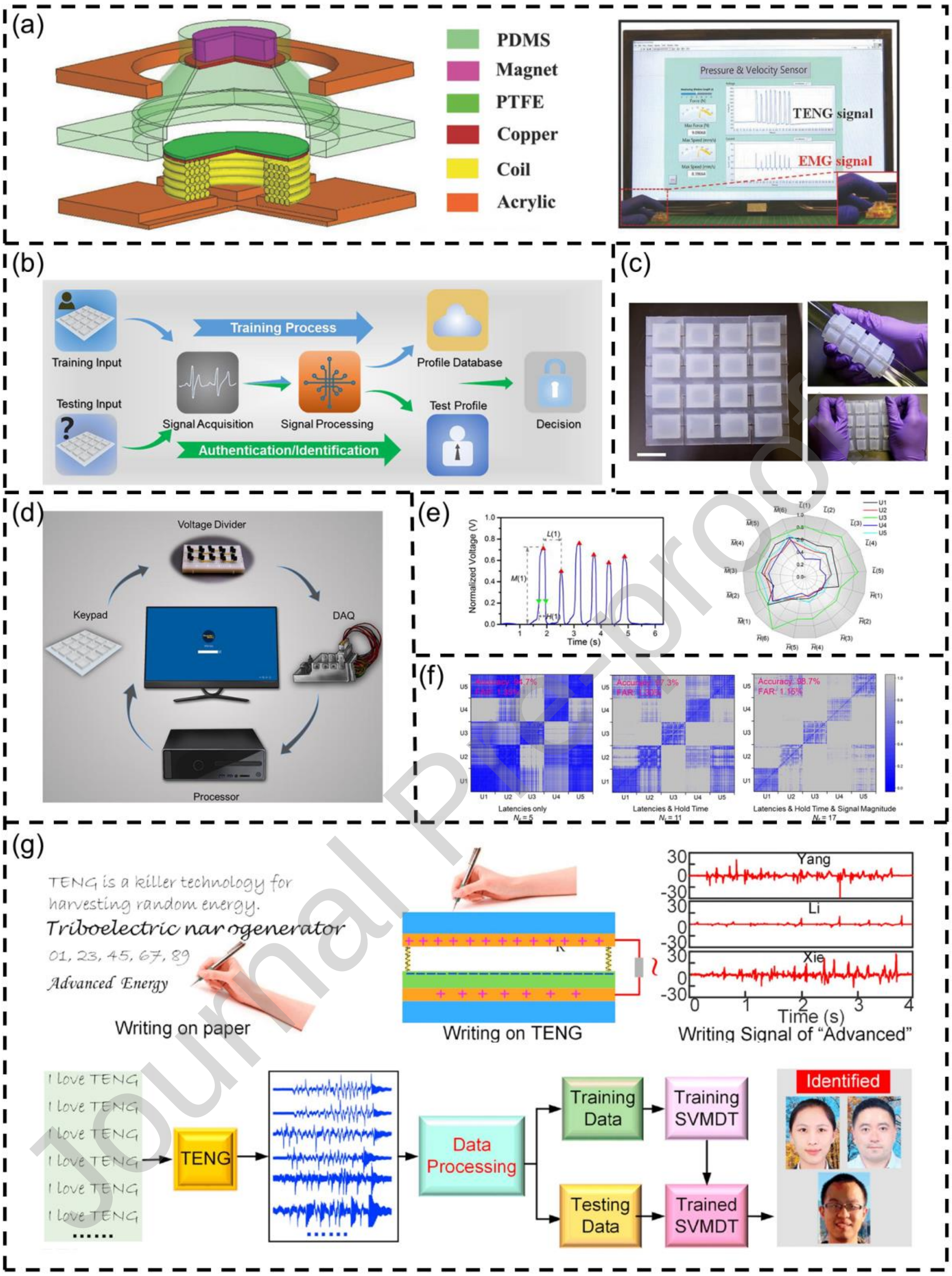

(a)
PDMS
Magnet
PTFE
Copper
Coil
Acrylic
Pressure & Velocity Sensor
TENG signal
EMG signal
(b)
Training Input
Training Process
Profile Database
Testing Input
Signal Acquisition
Signal Processing
Test Profile
Decision
Authentication/Identification
(c)
(d)
Voltage Divider
Keypad
DAQ
Processor
(e)
Normalized Voltage (V)
Time (s)
M(1)
L(1)
H(1)
U1
U2
U3
U4
U5
(f)
Latencies only
Latencies & Hold Time
Latencies & Hold Time & Signal Magnitude
Accuracy: 97.3%
Accuracy: 98.7%
FAR: 1.16%
(g)
TENG is a killer technology for
harvesting random energy.
Triboelectric nanogenerator
01, 23, 45, 67, 89
Advanced Energy
Writing on paper
Writing on TENG
Yang
Li
Xie
Time (s)
Writing Signal of "Advanced"
I love TENG
I love TENG
I love TENG
I love TENG
I love TENG
I love TENG
......
TENG
Data Processing
Training Data
Training SVMDT
Testing Data
Trained SVMDT
Identified

Fig. 5

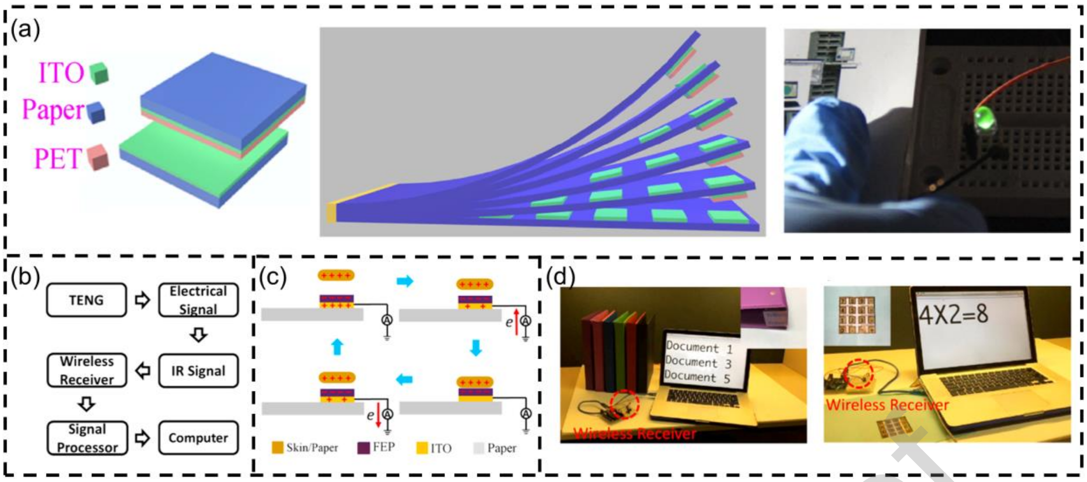

(a)
ITO
Paper
PET
(b)
TENG
Electrical Signal
IR Signal
Wireless Receiver
Signal Processor
Computer
(c)
e
e
Skin/Paper
FEP
ITO
Paper
(d)
Document 1
Document 3
Document 5
Wireless Receiver
4X2=8
Wireless Receiver

Fig. 6

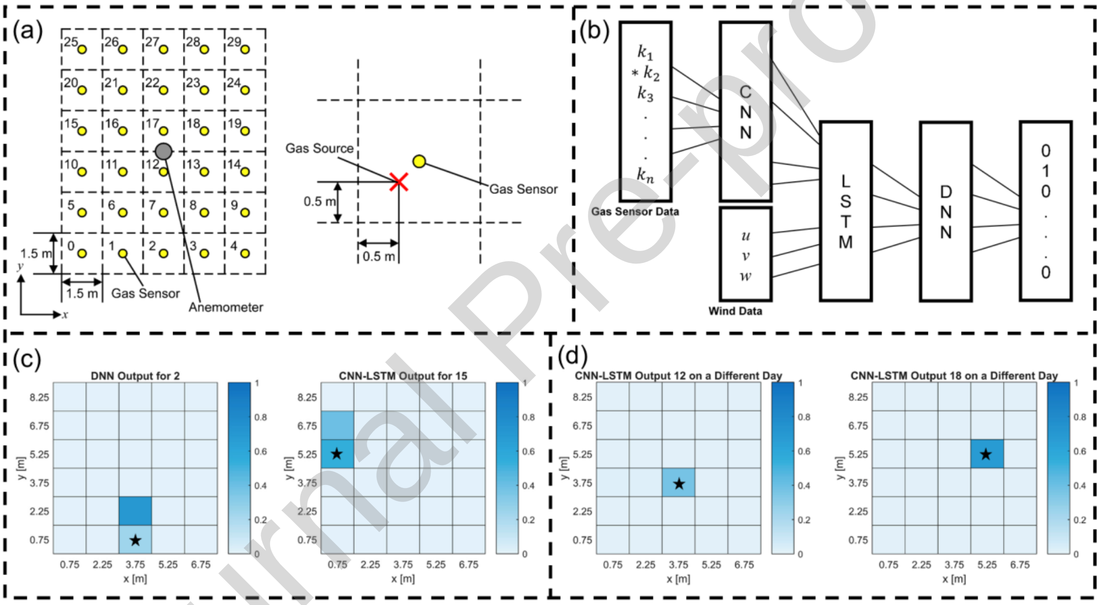
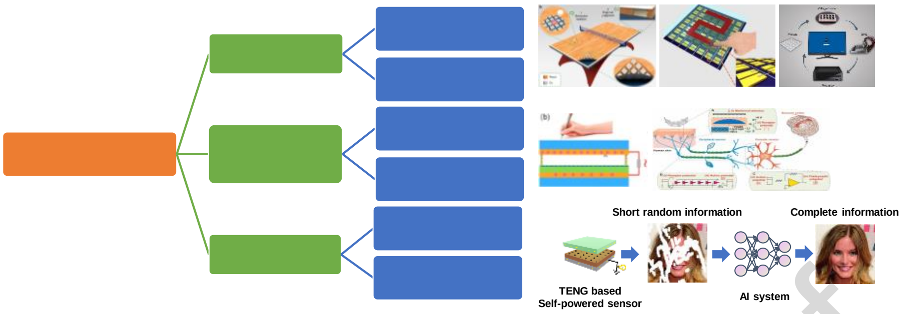

(a)
25 26 27 28 29
20 21 22 23 24
15 16 17 18 19
10 11 12 13 14
5 6 7 8 9
0 1 2 3 4
1.5 m
1.5 m
y
x
Gas Sensor
Anemometer
Gas Source
Gas Sensor
0.5 m
0.5 m
(b)
k_1
$* k_2$
k_3
k_n
Gas Sensor Data
CNN
u
v
w
Wind Data
LSTM
DNN
0 1 0 . . . 0
(c)
DNN Output for 2
CNN-LSTM Output for 15
(d)
CNN-LSTM Output 12 on a Different Day
CNN-LSTM Output 18 on a Different Day
y [m]
x [m]
0.75 2.25 3.75 5.25 6.75 8.25
0 0.2 0.4 0.6 0.8 1

Fig. 7

Graphical abstract



The review introduces the application capabilities and prospects of triboelectric nanogenerators (TENG) in intelligent sports, safety, touch control and document management systems. TENG based self-powered sensors are perfect for artificial intelligence (AI) applications in the future.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlight

1. TENG based sensor meet the energy supply challenge of artificial intelligence.
2. TENG based artificial intelligence is a new direction for sensor in the future.
3. TENG based artificial intelligence provides a brand-new idea for data collecting and process.