Intelligent Cubic-Designed Piezoelectric Node (iCUPE) with Simultaneous Sensing and Energy Harvesting Ability toward Self-Sustained Artificial Intelligence of Things (AIoT)

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ABSTRACT: The evolution of artificial intelligence of things (AIoT) drastically facilitates the development of a smart city via comprehensive perception and seamless communication. As a foundation, various AIoT nodes are experiencing low integration and poor sustainability issues. Herein, a cubic-designed intelligent piezoelectric AIoT node iCUPE is presented, which integrates a high-performance energy harvesting and self-powered sensing module via a micromachined lead zirconate titanate (PZT) thick-film-based high-frequency (HF)-piezoelectric generator (PEG) and poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)) nanofiber thin-film-based low-frequency (LF)-PEGs, respectively. The LF-PEG and HF-PEG with specific frequency up-conversion (FUC) mechanism ensures continuous power supply over a wide range of 10−46 Hz, with a record high power density of 17 mW/cm³ at 1 g acceleration. The cubic design allows for orthogonal placement of the three FUC-PEGs to ensure a wide range of response to vibrational energy sources from different directions. The self-powered triaxial piezoelectric sensor (TPS) combined with machine learning (ML) assisted three orthogonal piezoelectric sensing units by using three LF-PEGs to achieve high-precision multifunctional vibration recognition with resolutions of 0.01 g, 0.01 Hz, and 2° for acceleration, frequency, and tilting angle, respectively, providing a high recognition accuracy of 98%−100%. This work proves the feasibility of developing a ML-based intelligent sensor for accelerometer and gyroscope functions at resonant frequencies. The proposed sustainable iCUPE is highly scalable to explore multifunctional sensing and energy harvesting capabilities under diverse environments, which is essential for AIoT implementation.

KEYWORDS: artificial intelligence of things (AIoT), self-powered sensor, piezoelectric generator, machine learning, status monitoring

INTRODUCTION

The artificial intelligence of things (AIoT) concept is shaping the future of smart society. To establish a smart and eco-society, the massive distribution of sensor nodes is gradually becoming an essential requirement for enabling the seamlessly communicated sensory network.1,2 Owing to the revolution of various sensing technologies, the highly integrated monitoring system not only assists us to obtain comprehensive information from diverse environments but also offers the inspection and manipulation functions to the industrial production,3 transportation,4 and smart home applications,5 etc., as shown in Figure 1a. Current research has presented many multifunctional sensory systems with compact size. However, long-term sustainability is still a challenging issue for those battery-based systems.6 Hence, the AI-enabled sensory system with long-term sustainability is key for constructing the smart city.7,8
Energy harvesting research has increased over the past two decades to provide a green alternative for the sensor nodes by extracting energy from the ambient environment. In terms of wireless sensor node applications, several promising energy sources have been studied such as solar, thermal, wind, and vibration; harvesting energy from mechanical vibrations is one of the most promising technologies in microsystems applications. Mechanical vibrations from the environment such as biological movements, machines, bridges, vehicles, tunnels, and other civil equipment have better power generation capabilities due to their versatility, high power density, and abundant presence. Table S1 (Supporting Information) lists some of these vibrating entities, along with their corresponding vibration accelerations and frequencies. Based on the vibration frequency and acceleration level, they can be classified into three categories: low, medium, and high frequency. Typically, low-frequency (less than 30 Hz) vibrations are associated with bridge structures and human motion. Machines such as diesel engine, steam turbine generator, and 3-axis machine tool have major frequencies in the medium-frequency range (above 30 Hz and below 70 Hz). Machines and equipment with relatively high frequencies (above 70 Hz), such as washing machine, blender, automobile engine, and household electrical generator, have associated acceleration levels of 0.05 to 4 g. With respect to harvesting energy from different vibration sources, one of the main challenges is to develop effective miniaturized energy harvesters that cover a wide range of operating frequencies while stabilizing their output power at the milliwatt level. The electromagnetic, piezoelectric, and triboelectric based vibrational generators are the commonly deployed technologies to convert ambient vibration energy into substantial electricity for powering up the sensor nodes. An electromagnetic generator (EMG) based on Faraday’s law has the merits of low cost, easy maintenance, high current, and long-lasting durability, which is well-suited for the engineering field. However, EMGs normally require relatively larger space to realize relative motion between the magnet and coil so as to maintain high output power. In addition, the EMG output is subject to interference from external magnetic fields, making them unsuitable as sensors.
Triboelectric nanogenerator (TENG) with the great availability of triboelectrification materials provides more flexibility in design and applications, as such as energy harvesting, manipulation in robotic interaction, and training applications, as well as health monitoring, and automated driving. However, in terms of supporting the whole sensory system, the power density of many reported TENGs is still insufficient for those commercialized units.

The TENG can be used as energy harvester and self-powered sensor because of its self-generated surface charges due to mechanical vibrations and stimuli. Such dual functions attributed to the material advantage can lead to seamless and minimalist designs of the Internet of things (IoT) sensor nodes with energy harvesters and sensors building on the same material technology. In addition to TENG, the piezoelectric generator (PEG) can be used as the energy harvester and self-powered sensor depending on the usage scenarios. The common PEG design is a free-standing cantilever structure that can produce significant response only if the dominant ambient vibration frequency exactly matches the resonant frequency. This nature feature brings the constraint of using a PEG cantilever as a generic solution for scavenging energy from various vibration sources. To overcome this challenge, i.e., being able to operate in broad bandwidth, a number of solutions have been proposed, including multiple PEGs cantilever array, frequency tuning or multiple vibration modes, and nonlinear mechanisms. Furthermore, the second challenge of using the miniaturized energy harvester as the useful power supply to realize the self-sustained IoT sensor nodes is the deteriorated power generation during each vibration cycle at low resonant frequencies. For capturing vibration energy at low frequencies from a broadband environment and further boosting up the output power, a frequency up-conversion (FUC) strategy has been investigated, which can convert low-frequency ambient vibration into high-frequency self-oscillation of PEG cantilevers via several mechanisms: mechanical plucking, mechanical impact, and impulse-like magnetic forces to name a few. On top of the challenges in the structural designs of PEGs, materials also affect the output performance significantly, where the known options of piezoelectric materials have been studied, such as lead zirconate titanate (PZT), poly(vinylidene fluoride) (PVDF), aluminum nitride (AIN), and zinc oxide (ZnO). Among all these materials, PZT has a high piezoelectric constant and can be easily prepared in its pure state at a lower cost, making it the most commonly used for energy harvesting. While the brittle property of PZT ceramics makes it unsuitable for flexible applications. To overcome these disadvantages, alternatives like polymeric materials are being used in large deformation scenarios because of their flexibility. Among polymers, PVDF is the most suitable material for energy harvesting and sensing applications because of its chemical resistance, flexibility, biocompatibility, and considerable piezoelectric, ferroelectric, and thermoelectric properties. To realize the micro-/nanoscale PEGs with scalable manufacturability for future commercialization, wafer-level microfabrication with thin-film deposition is the main solution. However, the reported output power from microscale PEGs using a piezoelectric thin film is not attractive due to the limited polarization charge in the film of about 1 μm thickness. In contrast, a piezoelectric thick film prepared by the microfabrication technology becomes a favorable solution that enables the PEGs with high output power and miniaturized device volume. Further replacing the fragile silicon substrate with a more lightweight and flexible substrate provides better mechanical properties for PEGs and also offers the possibility for the development of self-powered wearable electronics. On the other hand, the PEGs are used as the power supply for the sensing units and/or IoT sensor nodes in most cases. As the piezoelectric output signal is also characterized as a function of parameter change, i.e., reflecting the ambient information, the piezoelectric self-powered sensors are reported for environmental monitoring and human-machine interaction. Flexible and affixable sensors made of PVDF nanomaterials were attached to the skin, specifically the throat, to monitor human behavior such as human movement, sound, and breathing. An active pulse wave sensing system has been applied to detect weak vibration patterns of the human radial artery. In addition, a PEG made of β-PVDF can be used as a self-powered acceleration sensor for real-time vehicle collision monitoring. Thus, by discovering more sensing functions from the PEG with a modular and universal design, the system complexity can be further reduced by removing unnecessary sensors. Because of using the piezoelectric self-powered sensors, the power consumption of IoT system can be further reduced. Briefly, this approach offers more possibilities toward a sustainable piezoelectric IoT system. For example, a tricylinder-like hybrid generator is capable of harvesting mechanical energy from various fluids and sensing real-time flow information for weather recording. However, due to the lack of in-depth data interpretation, these preliminary works can only show qualitative sensitive data. To boost the intelligence of data analytics of the IoT sensors, machine learning (ML) techniques have been used for AI-enhanced self-powered sensors, which enable the extraction of more useful data, e.g., gas moisture detection, gait analysis, and body motion sensing.

Here, we present an intelligent cubic-designed piezoelectric node (iCUPE) using highly integrated PEG and versatile triaxial piezoelectric sensor (TPS) for self-sustained IoT sensing system, where the data analytics are enhanced by cloud AI-computing. By using the FUC-based broadband mechanism, the iCUPE achieves record-high output power density over a wide vibration frequency range of 10–46 Hz at low and medium frequencies and 200–240 Hz at high frequencies, meeting the frequency range of most vibration sources. The cubic design allows for orthogonal placement of the three FUC-PEGs to ensure a wide range of response to vibrational energy sources from different directions. Generally, piezoelectric output signals from the low-frequency (LF)-PEG cantilevers in the iCUPE combined with AI-enhanced cloud computing achieves detection of acceleration changes, frequency shifts, and tilting angle variation at 0.01 g, 0.01 Hz, and 2° with accuracies over 98%. Unlike the conventional capacitive or resistive-based MEMS sensors that measure the variations of physical parameters via analog signals directly, the AI-enhanced iCUPE with multiparameter sensing function is accomplished by simply analyzing the dynamic piezoelectric output with relatively good sensitivity and accuracy. As a result, a multifunctional self-sustainable iCUPE is demonstrated for environmental monitoring and fault diagnosis, which can be adopted in various applications, including transportation, mining, industry, and smart home, to name a few. By massively distributing these iCUPEs, the self-sustained AIoT will be established and operated at a much lower cost.
Figure 2. (a) Characterization of LF-PEG, HF-PEG, and FUC-PEG; (i) top view of HF-PEG, (ii) side view of FUC-PEG, and (iii) top view of LF-PEG. (b) Microfabrication process of PZT thick-film and (c) SEM cross-section image. (d) Electrospinning process of P(VDF-TrFE) thin-film and (e) SEM image of P(VDF-TrFE) nanofibers. (f) Schematics of (i) self-powered sensing with the outputs from three LF-PEGs and (ii) self-powered sensing with the vibration along Z axis. (g) Multichannel outputs of iCUPE with 0.4 g acceleration and no tilting for the varied vibration frequencies of (i) 20 Hz, (ii) 40 Hz, and (iii) 60 Hz. (h) Multichannel outputs of iCUPE with 40 Hz frequency and no tilting for the varied accelerations of (i) 0.3 g, (ii) 0.5 g, and (iii) 0.7 g. The multichannel outputs of iCUPE with 40 Hz frequency and 0.4 g acceleration for a tilting angle of 45° along (i) X-axis and (j) X- and Y-axes.
RESULTS AND DISCUSSION

Design of the iCUPE. Targeting at the future AIoT enabled applications including smart mining, factory automation, industry 4.0, transportation, traffics, and smart city, and diversified low-frequency vibration sources are available. The iCUPE acts not only as a vibrational piezoelectric energy harvester to support the operation of IoT sensor nodes but also as a piezoelectric self-powered sensor for detecting the vibrations parameters associated with vehicle driving conditions and equipment operation conditions in smart city, i.e., intelligent mine, smart transportation, and so on (Figure 1a). The designed self-powered piezoelectric AIoT node, iCUPE, is shown in Figure 1b,c. The iCUPE adopts a three-dimensional (3D) hexahedron modular design with six replaceable sensing and functional modules located at six faces. In this work, the module configuration of this iCUPE is set as follows: a TPS module using three poly(vinylidene fluoride-co-trifluoroethylene) (P-(VDF-TrFE)) thin-film-based low-frequency (LF)-PEGs as the vibration sensing units, a temperature and humidity sensing module, a Bluetooth module, a core data processing module, and a frequency up-conversion piezoelectric generator (FUC-PEG) module consisting of a LF-PEG and a PZT thick-film high-frequency (HF)-PEG (Figure 1c, also can be seen in Figure S1, Supporting Information). Specifically, the LF-PEG unit is made...
by meander-shaped stainless-steel beam coated with P(VDF-TrFE) thin-film with a tungsten-based proof mass attached at the end. Three LF-PEG sensing units form an orthogonal structure by placing them at the adjacent faces, as shown in Figure 1c(i). In Figure 1c(ii),(iii), there are two faces for integrating the temperature and humidity sensing module, as well as the Bluetooth module. The core processing circuit with power management unit is placed at the center of iCUPE, as shown in Figure 1c(iv). The detailed design schematic of the core processing circuit can be seen in Figure S2 (Supporting Information). An as-fabricated FUC-PEG module is then placed at one face of iCUPE (Figure 1c(v)). The whole assembled iCUPE is a cubic shape with 6 cm side length. This modular cubic design ensures both the robustness of the system and the great compatibility toward different scenarios, hence, to fulfill various requirements of the AIoT ready smart city.

The two main modules of iCUPE are the TPS module and the FUC-PEG module. Figure 1b(ii) depicts the self-powered TPS with three LF-PEGs sensing units forming an orthogonal structure. The TPS is capable of sensing the surrounding vibration signals without additional power supply. These raw signals provide preliminary sensing information, such as frequency and acceleration. To further explore the hidden information, the sensing data is analyzed in conjunction by ML techniques. In addition, the implementation of multiple sensing channels can substantially improve the intelligence of the entire system by collaborative processing of the fused data, thus enabling the capability of artificial intelligence techniques. The FUC-PEG for harvesting surrounding vibration energy is shown in Figure 1b(iii). Due to the inherent characteristics of resonant-based vibration generators, a single PEG usually possesses optimal output power within a certain frequency range, which is too narrow for diverse applications. Hence, to further broaden the operational frequency range, the FUC mechanism is adopted by integrating a LF-PEG to couple with a thick-film HF-PEG, realizing the conversion from low-frequency excitations to high-frequency self-oscillations while achieving the broadening of frequency bandwidth as well. Among them, the flexible LF-PEG is made by electrostatically spinning P(VDF-TrFE) nanofibers on a steel substrate, while the HF-PEG is formed by microfabrication of a bimorph thick-film PZT with a sandwiched copper substrate.

**Characterization of Self-Powered Sensing of the TPS.**

For the AIoT concept, the most important function is to perform sustainable sensing from the environmental variations. Current MEMS sensors usually operate at nonresonant mode with a certain power consumption. As a sustainable AIoT sensor node, utilization of self-powered sensor is preferable for extending the operation lifetime. As mentioned above, the iCUPE contains two main modules, including TPS for sensing and FUC-PEG for energy harvesting. The direct piezoelectric effects from both TPS and FUC-PEG are able to convert mechanical vibration stimuli into electrical signal and energy outputs, respectively.

The design of FUC-PEG consisting of a LF-PEG and a HF-PEG stacked together with adjustable gap is shown in Figure 2a. The resonant frequency of LF-PEG can then be adjusted by changing the end proof mass, and the detailed design parameters can be seen in Figure S3 (Supporting Information) and Table S2 (Supporting Information). To improve the power generation capability of HF-PEG, a bimorph PZT cantilever was microfabricated by low-temperature bonding of two thinned PZT thick-films on a copper substrate (Figure 2b,c). Unlike conventional sputtering or sol–gel-based processes that can only fabricate piezoelectric films of a few microns, our proposed low-temperature bonding, mechanical thinning, and laser cutting processes can provide piezoelectric thick-film of tens of microns, possessing 40–100 times higher output performance. To realize the sensing capability of LF-PEG, a meander-shaped flexible cantilever with P(VDF-TrFE) nanofiber thin-film on a stainless-steel substrate was fabricated by electrospinning (Figure 2d). Figure 2e shows the SEM images of the P(VDF-TrFE) nanomaterials.

The TPS consisting of three LF-PEGs is used as a self-powered vibration sensor. The three-channel sensing signals of the TPS are characterized in Figure 2f−j. The green, blue, and red lines indicate the output voltages of the three LF-PEGs perpendicular to the X-axis, Y-axis, and Z-axis, respectively. Figure 2f(ii) shows the iCUPE without tilt subjected to vibration excitation along the Z-axis. In Figure 2g, the output voltages of the three LF-PEGs were tested at different vibration frequencies of 20, 40, and 60 Hz. It is seen that the maximum amplitude of output voltage for all three channels is at 40 Hz, which is the resonant frequency of LF-PEG (Figure 2g(ii)). The frequency differences can be clearly distinguished via the period variations of output waveforms, which is the basis for accurate frequency identification by the TPS. Similarly, in Figure 2h, for a given frequency of 40 Hz, the increase in acceleration shows a significant increase in the sensing output, so that the acceleration magnitude can be identified as well. In addition, in Figure 2i,j, the iCUPE is tilted by 45° along the X-axis and Y- and Z-axes, respectively, and the vibration excitation is constant along the Z-axis, with a tested frequency and acceleration of 40 Hz and 0.4 g. Compared to the output in Figure 2g(ii), the variations in Figure 2i(ii),j(ii) are evident from the output signals of channel X and channel Y. The tilting angle along the X- and Y-axes leads to a significant increase in the output voltages of LF-PEG X and LF-PEG Y, due to the better mechanical response of the tilted LF-PEG plane for a given excitation direction. It shows that the trend of the voltage amplitude of each channel can also reflect the tilting angle.

**ML-Enabled Intelligent Sensing of the TPS.**

With the AI-enhanced cloud computation, the amplitude variations of the output voltages of the TPS can be used to accomplish the multipurpose identification of frequency, acceleration, and angle based on ML algorithm. As shown in Figure 3a, the TPS located at three faces of iCUPE acquire the vibrational signals from the external stimuli, and then, these signals can be recognized by the trained Convolutional Neural Networks (CNN) model for defining the operation status of the equipment and sending back to the user wirelessly. At the model training stage for ML, each data set contains 150 samples with 100 data points. Among them, 120 samples are used for training and 30 samples are used for validation. The basic structure of the applied CNN is depicted in Figure 3a(i), as well as the typical output signals of the three LF-PEGs under the specific vibration status. It is clear that, for each test, e.g., the acceleration detection, the multiple outputs from LF-PEG sensors for a specific acceleration possess a different pattern that can be differentiated. Noticeably, the design of three LF-PEG sensors with perpendicular placements ensures strong signal response to the stimuli from different directions and, hence, offers reliable performance during practical applications. As shown in Figure 3b, the recognition capability of TPS has been tested and validated to be effective in the acceleration range 0.1−0.8 g, frequency range 20−60 Hz, and tilting angle range ±40° for the application scenarios of machines and equipment status monitoring. As the primary
characterization, the ML-assisted recognition of acceleration, frequency, and angle were tested at the resonant frequency (\(\sim 40\) Hz) of the sensors. In Figure 3c(i)–(iii), according to the confusion map of the corresponding tests, the TPS is able to detect the acceleration, frequency, and tilting angle with resolutions of 0.01 g, 0.01 Hz, and 2°, respectively. A comparison of the performance parameters and functional features between the iCUPE and some MEMS-based accelerometers, gyroscopes and tilt sensors is listed in Table S3 (Supporting Information). An obvious breakthrough is seen of the proposed iCUPE in combining with ML to accomplish multiparametric intelligent sensing. The recognition accuracies can reach to 98%–100%, owing to the feature of multichannel inputs from the LF-PEG sensors of different faces. Instead, the comparison tests were conducted by using a single LF-PEG sensor for recognition. As shown in Figure S4 (Supporting Information), three LF-PEG-based recognitions shows obvious advantages compared to those of the single sensor. First, the recognition accuracies of three LF-PEG sensors are the highest for all scenarios. Second, for a single sensor, only the one that is perpendicular to the vibration direction can give relatively good accuracy. In another word, the single channel design may not operate properly when the vibration direction is altered. To intuitively reveal the discriminatory capacity of TPS and the
consistency and variability among the data sets, 2D t-SNE maps were obtained by projecting the high-dimensional sensory responses into the two-dimensional (2D) space via t-distributed stochastic neighbor embedding (t-SNE), as shown in Figure S5 (Supporting Information). It can be seen that the reduced-dimensional data can naturally form distinctive clusters, and there are demarcation lines between different clusters, indicating that the data sets under different accelerations, frequencies, and tilting angles are easily distinguishable, and high recognition accuracy can be obtained with the help of the CNN algorithm. Figure S6 (Supporting Information) indicates that the recognition accuracy at resonant frequency is the optimal choice for the LF-PEG sensor design.

Characterization of Frequency Response of the FUC-PEG. The TPS relies on the piezoelectric effect to accomplish its own self-powered sensing function, while the FUC-PEG is used to generate power to support the other modules of iCUPE, such as the Bluetooth module and temperature and humidity sensing module. The working mechanism of the FUC-PEG is shown in Figure 4a−c, which demonstrates the motion of LF-PEG and HF-PEG in a typical single-cycle impact, including excitation, collision, and oscillation stages. During the excitation stage
(Figure 4a), the LF-PEG is activated by an external stimulus and generates large amplitude oscillations at frequencies close to the resonance frequency, while the HF-PEG has a much lower amplitude due to the huge deviation from the resonant frequency, and the waveform is shown in Figure 4d(i). Once the oscillation amplitude of LF-PEG exceeds the gap between two PEGs, the collision stage is initiated (Figure 4b). The upward motion of LF-PEG is constrained, and hence, the overall stiffness will increase along with the displacement. Eventually, the resonant frequency of LF-PEG increases subsequently to achieve broadband operating frequency (Figure 4d((iii)). After a short period of time, the LF-PEG and HF-PEG are separated as shown in Figure 4c. The LF-PEG is forced to oscillate downward, while the HF-PEG with a higher frequency is experiencing periodical free oscillation. The whole process realizes the conversion from low-frequency excitation of LF-PEG to high-frequency oscillation of HF-PEG. The waveform of the collision stage in the red region shows periodical instantaneous spikes in Figure 4d(ii), followed by the periodical high-frequency decayed oscillations in the teal region in Figure 4d(ii). It is worth mentioning that the broadening of frequency is generally determined by the increasing of effective stiffness and the decreasing of damping coefficient. However, the higher stiffness will also induce a higher damping coefficient. Moreover, the gap distance can affect the operation bandwidth and the output voltage.

To evaluate the frequency response of the FUC-PEG in the as-fabricated iCUPE, experiments were conducted, and the detailed test setup are shown in Figure S7 (Supporting Information). In Figure 4e, the open-circuit voltages of individual LF-PEG and HF-PEG were tested under the respective frequency spectrum. The LF-PEG generates a maximum output voltage of 2.5 V at 31 Hz, while the HF-PEG produces a significant output of 28.5 V at 214 Hz. With the help of the FUC mechanism, the integrated FUC-PEG has an effective operating frequency range of 25–40 Hz and is capable of generating open-circuit voltage of 48 V at low-frequency conditions. As a result, the output voltage of the FUC-PEG is not only 1.7 times higher than that of the HF-PEG operating at high-frequency conditions but also even 19 times higher than that of the LF-PEG operating at low-frequency conditions, greatly enhancing the overall output. The output waveform in time domain is also given in Figure 4f. As can be seen, the engagement between the HF-PEG and LF-PEG generates an instantaneous voltage peak, and then, the oscillated output gradually decays until the next engagement. In practical applications where low-frequency oscillations dominate, this design not only effectively reduces the operating frequency from above 200 Hz to a few tens of Hz with the broadband operation frequency but also increases the output voltage at low-frequency conditions by more than a factor of 10 through the FUC mechanism. In Figure 4g,h, the output characteristics of the FUC-PEG for the combinations of LF-PEGs with resonant frequencies of 24, 31, and 40 Hz and HF-PEG with a resonant frequency of 214 Hz were tested. The testing results show that, the lower the resonant frequency of LF-PEG, the higher the open-circuit voltage of FUC-PEG. The higher the resonant frequency of LF-PEG, the wider the operating bandwidth of FUC-PEG. As a compromise, the LF-PEG of 31 Hz is selected for the next characterization.

The acceleration magnitude of the external excitation and the gap distance between LF-PEG and HF-PEG affect the output performance of the FUC-PEG. Frequency sweep tests were performed at different accelerations of 0.1, 0.3, 0.5, 0.8, and 1.0 g, respectively, as shown in Figure 4ij, with a fixed gap distance of 0.5 mm. The results indicate that, for a given FUC-PEG, both operation bandwidth and peak output voltage increase along with the increasing of acceleration. This is because the higher the acceleration, the wider the frequency range over which the LF-PEG amplitude can reach 0.5 mm, thus achieving a wider frequency bandwidth. The output voltage of the HF-PEG depends on its amplitude, which is mainly related to the collision force. The higher the acceleration, the higher the collision force, and the higher the instantaneous output voltage of HF-PEG. Additionally, for a fixed acceleration of 1.0 g, the outputs of FUC-PEGs for gap distances of 0.5, 1, 1.5, 3, and 5 mm were tested (Figure 4kl). As the gap distance increases, the excitation frequency should be closer to the resonant frequency of the LF-PEG to make contact with the HF-PEG, so the operation bandwidth decreases as the gap between LF-PEG and HF-PEG increases. A wide frequency range of 10–46 Hz can be covered for a gap distance of 0.5 mm. However, in the case of variable gap distance, the collision force is related to multiple factors, including the velocity at the time of collision, the contact time, and the phase difference between LF-PEG and HF-PEG motions, hence showing the low correlation between the gap distances and the open circuit voltages. It is also worth investigation in future study. Overall, the open-circuit voltage increases and then decreases with the gap distance, with a small fluctuation range in between. A high output voltage (42.8 V) and a wide frequency bandwidth (21 Hz) are obtained simultaneously at a gap distance of 1 mm, which is the current optimal parameter. The time domain open-circuit voltage waveforms of the FUC-PEG under different conditions corresponding to Figure 4ijk are shown in Figure S8 (Supporting Information). To investigate the long-term stability of the energy harvesting, the open-circuit voltage of FUC-PEG was tested at the resonant frequency of 214 Hz for HF-PEG and 31 Hz for LF-PEG, respectively, under a vibration acceleration of 1 g for 90 min, and the results are shown in Figure S9 (Supporting Information). It is obvious that FUC-PEG has high stability during this test period, and the waveforms of both pre- and postvibration matched well. Overall, this FUC and tunable HF/LF-PEG design allow for a wide coverage of operating frequencies for various conditions with long-term stability.

Characterization of Output Power of the FUC-PEG. In addition to the broadband performance of the FUC mechanism, the power generation capability of the FUC-PEG is then evaluated as shown in Figure 5. For fabricating the FUC-PEGs, three pairs of HF-PEGs and LF-PEGs are used, including (1) FUC-PEG I, 209 Hz HF-PEG + 31 Hz LF-PEG, (2) FUC-PEG II, 214 Hz HF-PEG + 24 Hz LF-PEG, and (3) FUC-PEG III, 218 Hz HF-PEG + 40 Hz LF-PEG. The peak power of three HF-PEGs with resonant frequencies of 209, 218, and 214 Hz was tested at an acceleration of 1 g and could reach 0.6, 0.5, and 0.5 mW, respectively, as shown in Figure S10 (Supporting Information). After combining the LF-PEGs and HF-PEGs to form the FUC-PEGs with 1 mm gap, three FUC-PEGs can generate maximum powers of 2.1, 2.6, and 1.3 mW, respectively (Figure 5a), at 1.0 g acceleration during the frequency sweep test, with a load resistance of 350 kΩ. Among them, FUC-PEG I has the highest power density of 17 mW/cm² at 37 Hz, and the maximum normalized power density can reach to 0.5 mW/cm²/g/Hz. The effective volume of the FUC-PEG is the sum of the volumes of the piezoelectric cantilever of the HF-PEG and the meander-shaped cantilever of the LF-PEG. Figure 5h shows the comparison of the normalized power densities of the reported
works (details are listed in Table S4, Supporting Information). The maximum normalized power density of a single HF-PEG is 0.04 mW/cm$^3$/g/Hz and that of the FUC-PEG is 12 times higher, which shows the great superiority of FUC-PEG compared with a single HF-PEG in terms of power generation. Not only that, the normalized power density of the proposed FUC-PEG is also tens or even hundreds of times higher compared with other PEGs reported in most works; meanwhile, it can also achieve broadband output, showing superior output performance in harvesting low-frequency vibration energy. These features are essential for scavenging the vibration energy to support the environmental monitoring.

For a vibrational energy harvester, the orientation and placement are important factors, which may significantly affect the power generation efficiency. The multiple PEGs with optimized orientations can improve the general output performance under various working conditions. Owing to the cubic structure of iCUPE, three FUC-PEGs can be aligned on three planes, e.g., $x$--$y$ plane, $x$--$z$ plane, and $y$--$z$ plane, as shown in Figure 5b. In this case, the direction of the vibration is perpendicular to the plane of FUC-PEG I, and hence, it shows good output power from 30 to 38.5 Hz, with a half-bandwidth of 8.5 Hz, and a maximum power of 2.6 mW at 37 Hz. Whereas, the FUC-PEG II and III on other faces give negligible outputs as they are parallel to the vibration direction, and the LF-PEGs at the first order resonant frequency cannot impact with the HF-PEGs. However, due to the design of the meander-shaped cantilever, the LF-PEG at the second order resonant frequency of 24 Hz can activate the torsion, which allows it to engage with the HF-PEG and realize the power generation from 49.6 to 59.6 Hz. Next, the iCUPE is tilted 45° along the $x$- and $y$-axes as illustrated in Figure 5c and makes all six faces form a 45° tilting angle against the vibration direction. In this case, all of the three FUC-PEGs can generate outputs based on the specific orientations. This combination ensures continuous output power over a wide range from 10 to 46 Hz. The output power of three FUC-PEGs can reach a maximum value of 2.3 mW at 27.7 Hz. Although the deviation from the vibration direction

![Figure 6. Demonstration of iCUPE assisted monitoring of the vehicle driving. (a) Photos and schematics of the system design. (b) (i) Graphical user interface for recognizing the driving status based on the output signals from the LF-PEGs and (ii) the confusion map of the recognition for different driving status. (c) Real-time signals and photos at different driving status during a complete application scenario.](https://doi.org/10.1021/acsnano.2c11366)
caused by tilted iCUPE may lower the output performance of the individual FUC-PEG, the total output power is still showing a noticeable enhancement.

In Figure 5d, the FUC-PEG I was tested at excitation of 1.0 g and 44 Hz for charging the capacitor after the rectifier. The FUC-PEG I can charge 10, 100, 220, and 330 μF capacitors to 5 V within 2, 19, 53, and 68 s, respectively. This high-power generation and charging capability enable the establishment of a self-sustainable AIoT system through the integration of power management unit and data transmission module. Moreover, as mentioned earlier, the iCUPE with modular design is capable of replacing the six faces with the necessary modules, e.g., sensors or PEGs. Therefore, the test of multiple FUC-PEGs was also performed to further prove the potential of boosting the power supply. Two FUC-PEGs with similar parameters were connected in parallel and series to charge the 330 μF capacitor, as depicted in Figure 5e,f. The power generation data of both FUC-PEG I and I’ shows similar charging speeds, where the capacitors were charged up to 5 V within 68−78 s. The charging speed was then accelerated by connecting two FUC-PEGs in parallel and series. Until the voltage of the capacitor reaches 8.5 V, the parallel connection charges faster compared to the series connection. However, after 8.5 V, the series connection has a faster charging rate and can eventually charge the capacitor with

Figure 7. iCUPE enabled wireless sensory system for establishing a digital twin mine to monitoring the underground working condition. (a) Schematics of the digital twin realized by the massive deployment of the iCUPEs. System design for monitoring the working status of the mining equipment, with (b) the mimicked on-site monitoring of the working environment, and (c) the duplicated virtual working environment using the sensing signals and the digital twin concept. Screenshots for the real-time digital twin assisted monitoring of various working conditions, including (d) normal conditions for frequency, acceleration, and tilting angle, alarm for frequency and acceleration, (f) normal conditions for tilting angle, overload warning for frequency and acceleration, and (g) overload warning for frequency, acceleration, and tilting angle.

https://doi.org/10.1021/acsnano.2c11366
ACS Nano XXXX, XXX, XXX−XXX

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more power. Overall, the series connection is slower in the early stages of charging but provides more power in the final stages. This phenomenon can be verified by the output signals obtained with parallel and series connections, as shown in Figure 5e. According to Ohm’s law, the total internal resistance decreases after parallel connection, and the output voltage is equal to the larger voltage of the two FUC-PEGs, so the parallel current increases. For series connection, the output voltage is the sum of the voltages of the two FUC-PEG, while the total internal resistance after series connection is summed as well, so the current remains unchanged. Eventually the output voltage of the two FUC-PEGs connected in series is higher than that of the parallel connection, but the current of the parallel connection is larger than that of the series connection. To demonstrate the power supply in practical application, a wireless temperature and humidity sensing module was integrated into the iCUPE, as shown in Figure 5g(i); the sensing module can be activated after the voltage of the capacitor reached 5 V, and then, the sensing data can be transmitted into the mobile terminal via Bluetooth within a time interval of 46 s (Figure 5g(ii),(iii)), which shows the feasibility of realizing a self-sustained sensor node.

Demonstration of the Vehicle Status Monitoring Using iCUPE. The massive distribution of the self-sustainable AIoT sensor nodes brings evolution toward to human society by establishing smart world with intelligent perception. Especially for industrial productivity, mining, and transportation, etc., the deployment of those sensor nodes can significantly improve efficiency and safety of the working environment. The experimental result of ML enables intelligent sensing of iCUPE for the practical applications. The highly integrated design and the robust package ensure the individual operation under diversified scenarios, such as the driving status monitoring of vehicles.

As an integrated demonstration for practical application, the iCUPE was attached on the vehicle engine to identify the driving status, including parking, accelerating, deaccelerating, bumping, uphill, and downhill (Figure 6a). The vibration of the operating engine can first be used as an energy source for the FUC-PEG to generate power to supply the iCUPE. In the meantime, the variations of the engine vibrations during the above-mentioned various driving status can also be obtained by LF-PEG sensors. To train the model for driving status recognition, 100 samples (500 data points per sample) from three sensing channels were collected for each state. In Figure 6b, a graphical user interface was developed for identifying the driving status based on the ML-enabled data interpretation for the sensing signals from iCUPE. Both of the original output signals and the recognized driving state can be displayed for driving assistance and monitoring of the vehicle. In general, according to the training model (Figure 3a), the accuracy of the recognition for the six predefined driving states can reach above 93%. The demonstration video of the real driving test can be seen in Video S1; the real-time sensing signals and recognized driving status are shown in Figure 6c. The sensing signals of each channel can be seen more clearly in Figure S11a (Supporting Information). At the parking state, there is almost no signal since the engine is not started. At the acceleration state, the cycling of the engine is suddenly boosted up; the entire engine is then generating stronger vibration. At the deacceleration state, the engagement of the brake can cause another mechanical shock in the reverse direction due to the inertia and, hence, also result in strong vibration, but with the enhanced output from another sensor, which is shown in red. When the vehicle is driving across a bumper, the bumping effect can cause the shaking of the whole body of the suspension system. Therefore, the cyclic pattern of the vibrational signals can be observed at this state. For the uphill and downhill states, the pressing on the gas pedal and the brake pedal will induce fluctuations of the vibration. Figure S11b (Supporting Information) shows the 2D t-SNE map for the data set obtained from six different driving states. It can be observed that the data of different driving states can naturally form distinctive clusters after dimensionality reduction, proving that the iCUPE is a reliable discriminative medium. This demonstration proves the flexibility of the deployment of iCUPE for diverse monitoring applications.

Demonstration of Digital-Twin-Based Monitoring in Harsh Environment Using iCUPE. Additionally, the mining environment is usually considered as an extreme working condition with the high level of potential hazards. The expected monitoring system needs to detect not only the environmental status, such as gas, temperature, and humidity, but also the operation status of different mining equipment. On the other hand, for a better understanding of the real-time situation through visualized media, the digital-twin-based reconstruction of the working environment is highly desired to improve the assessment and the management of production and potential risks. The proposed iCUPE can then act as the sensor node, which is available for massive deployment in the harsh environment and establishing industry AIoT to collect necessary multimodal information. As illustrated in Figure 7a, a wireless sensory system designed for the underground mining environment is implemented by the multiple iCUPEs. These iCUPEs can cooperate to develop the digital twin mine for status monitoring and risk assessment of the mining equipment and environment condition.

In Figure 7b,c, a basic schematic about the operation principle of the proposed digital-twin-based monitoring system is illustrated. In real-space shown in Figure 7b, the shaker with tunable vibration frequency and acceleration was applied to mimic the vibration from the mining equipment, e.g., pump. At the initial stage, the training data were collected by iCUPE and wirelessly sent to cloud server for model training using ML algorithms. Once the model was built, the collected sensing data can then be used for the real-time recognition of working conditions. In the meantime, a virtual working environment is duplicated for realizing the digital twin-based visual monitoring (Figure 7c). As can be seen in the virtual space, an iCUPE was installed onto the shell of the pump to detect the equipment status via vibration signals, while the monitoring interface displayed the sensing signals and the operation status. The relationship between the real and virtual spaces can also be seen in Figure S12 (Supporting Information).

The performance of the iCUPE-based monitoring system was tested under varied operation status, including vibration frequency, acceleration, and tilting angle. The experimental results are shown in Figure 7d–g, including (d) frequency, 20 Hz, acceleration, 0.3 g, no tilting; (e) frequency, 40 Hz, acceleration, 0.5 g, no tilting; (f) frequency, 60 Hz, acceleration, 0.8 g, no tilting; and (g) frequency, 20 Hz, acceleration, 0.3 g, tilting angle, 45° at X- and Y-axes. The respective status of the frequency/acceleration and the tilting angle are indicated separately for better risk assessment. For instance, in Figure 7c, once the acceleration of the pump exceeds 0.5 g, and the vibration frequency reaches 40 Hz, the yellow light is turned on, and the alarm will be sent to the monitoring terminal immediately. When the acceleration of the pump exceeds 0.8
g and the vibration frequency reaches 60 Hz (Figure 7f), the light turns into red, indicating the risk of failure occurs. In Figure 7g, once the pump is experiencing tilting or heavy shaking, the monitoring system will not only send the alarm but also cut the power supply to avoid an accident. According to the ML-based recognition results, all of these operation statuses can be distinguished with high accuracy of 100% (also can be seen in Figure S13, Supporting Information and Video S2, Supporting Information).

Hence, by expanding the distribution of iCUPE to form the AIoT ready smart city, the working conditions of equipment and environment can be continuously monitored. The iCUPE-based sensor network can be the basic infrastructure of the AIoT. Together with the digital twin technique and other self-powered sensors, e.g., chemical sensors, gas sensors, etc., the proposed system shows great potential in a remote area or harsh environments, as well as other fields, such as tunnel, chemical industries, etc.

CONCLUSION

Owing to the emerging concept of AIoT, the development of diversified sensory nodes with high intelligence is experiencing rapid advancement, which may benefit various fields, such as smart home, industry 4.0/5.0, and smart city, etc., through the exchange of comprehensive information. However, massive distribution of those AIoT nodes brings the issue of the maintenance, such as battery replacement. The energy harvesting technology is then drawing great attention to enable a self-sustainable sensory node. With the aid of FUC-PEG of high power density and the piezoelectric thick-film microfabrication and thin-film electrosputtering process, the iCUPE can offer both power generation and multifunctional sensing capabilities, e.g., temperature, humidity, vibration, acceleration, tilting angle, etc. In terms of power generation from the random vibration sources, the design of FUC-PEG gives not only broadband effects of 10 to 46 Hz but also the boost of energy harvesting efficiency. At the acceleration of 1 g and excited frequency of 37 Hz, the power density of the FUC-PEG can reach to 17 mW/cm². Besides, the cubic design allows for orthogonal placement of the three FUC-PEGs to ensure a wide range of response to vibrational energy sources from different directions. The broadband, high power characteristics, and flexible orientations of iCUPE can support its wide range of applications in scenarios with different operating frequencies and usage.

To further minimize the system complexity by exploring more functions from the proposed iCUPE, the ML algorithm is adopted to analyze the three-channel signals of the TPS for analyzing the operation status of the vibration sources, e.g., vehicle and industrial equipment. Overturning the traditional sensing device with sophisticated and fine structure design, this proposed iCUPE with the ML technique can detect various parameters around the resonant frequency. The fusion of three channel signals can further improve the recognition accuracy compared to that of the single channel. The TPS provides relatively high detection resolutions of acceleration of 0.01 g, frequency of 0.01 Hz, and tilting angle of 2°, with recognition accuracies of 100%, 98.89%, and 100%, respectively. This work indicates the possibility of applying the ML-based intelligent sensor around resonant frequency to achieve the functions of the accelerometer and gyroscope. To further verify the feasibility of the ML-based sensing and FUC-based energy harvesting of the iCUPE, the monitoring of the operation status for the vehicle and the mining equipment are demonstrated. Noticeably, the demonstration of the monitoring system for the underground mining illustrates the basic infrastructure of integrating sustainable AIoT with the digital twin technique, which is the future trend to many industry segments.

METHODS

Fabrication of the HF-PEG: First, the conductive epoxy (DAD-91L) was screen printed on the surface of the polished PZT ceramic chip (C-6, Fuji); then, the two printed PZT chips were attached to the top and bottom surfaces of the double-sided polished copper sheet. It was then heated at 150 °C and bonded with a pressure of 0.1 MPa in a vacuum chamber for 5 h. Each side of the bonded bimorph PZT chip was then thinned down to 70–100 μm using a grinding and polishing machine (UNIPOL-1203, KEJING). The electrodes were formed by sputtering 50 nm Cr and 950 nm Al on the top and bottom surfaces, respectively, using a magnetron sputter machine (MSP-300B, Chuangshiweina Technology). Afterward, the shape of the cantilever was released by laser cutting, and a tungsten proof mass was bonded to the end of the cantilever.

Fabrication of the LF-PEG: A stainless-steel sheet with meandering-shape was used as the substrate and bottom electrode. The P(VDF-TrFE) was dissolved in a mixture of N,N-dimethylformamide (DMF) and acetone with a volume ratio of 1:1 for suitable viscosity and volatility. The obtained suspension was then electrosprun directly onto the substrate by electrostatic spinning (PANSEPRAN PS-1) to form a homogeneous thin-film P(VDF-TrFE) nanofibers. After that, Cr/Cu was magnetron sputtered on the P(VDF-TrFE) film as the top electrode. A tungsten mass was fixed at the end of the beam to reduce the resonant frequency.

Design of core circuit: The core circuit consists of a power management circuit for the FUC-PEG and a signal processing circuit for the LF-PEGs. The power management circuit contains a commercial power management unit (LTC3588-1) for rectification and voltage regulation. The output of the LTC3588-1 was first connected to a small capacitor, which was then connected to a super capacitor that could be automatically charged when the voltage of the small capacitor reaches a threshold value. A microcontroller (ATMEGA328P-AU) was used for signal acquisition, processing, and transmission. The output voltage generated by the three LF-PEGs was first boosted by a 2.5 V regulator (AMS1117-2.5 V), which is then connected to the analog input of the microcontroller to obtain the output signal, which is sent to the PC via the Bluetooth module.

Fabrication and assembly of iCUPE: The main structure of the highly integrated PEG-based intelligent wireless sensing node (iCUPE) consists of a cube support base, a customized core circuit, three LF-PEGs, a FUC-PEG, a commercial temperature and humidity module (CYALKIT-E03), and a commercial Bluetooth module (HC-05); all of these modules were equipped with the protective housings, respectively. All of these bases and housings were fabricated by 3D printing (Shape 1, Rayshape). The core circuitry was fixed inside the cube support base using screws and nuts, while the remaining modules and the protective housing were glued to each of the six concave sides of the cube support base.

Characterization of PEG output: The output performance of the FUC-PEG and the LF-PEG sensing performance was tested by using a vibration shaker (TV S11110, TIRA). The piezoelectric output of the FUC-PEG, the voltage was measured and recorded by a dynamic signal analyzer (m+p VibPilot) and vibration control and analysis software (m+p Toolbox 2.12.22.0). The voltage of the capacitor charged by the FUC-PEG was measured by an oscilloscope (DSO-X 3032 T, Infinivision, Agilent). The piezoelectric sensing signals from the three-channel LF-PEG were acquired in real time by a signal acquisition module using ATMEGA328P-AU microcontroller.

Demonstration of vehicle monitoring: Two cars (SVW6432KGD, SKODA and 3008, PEUGEOT) were used for the demonstration. The iCUPE was fixed to the car engine, and the voltage data of the LF-PENGs in different driving states were acquired through the ATMEGA328P-AU microcontroller. The acquired electrical signals were sent instantaneously to a laptop computer via the Bluetooth.
module, and the received signals were used for driving state recognition via a trained CNN model.

Demonstration of the digital-twin-based monitoring of the mining environment: The signal acquisition module in iCUPE acquired the three-channel piezoelectric signals of the LF-PEGs under different excitation conditions via the ATMEGA328P-AU microcontroller. The acquired electrical signals were sent instantaneously to a laptop via the Bluetooth module. The received signals were processed by a trained CNN model. The output of the recognition was sent to Unity 3D via TCP/IP to synchronize the pump machine vibration in virtual space.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.2c11366.

Tables of frequency and acceleration levels of different vibration entities, design parameters of the HF-PEG and LF-PEG, comparison of performance parameters and features between MEMS-based sensors and iCUPE, and comparison of the output performance between previously proposed piezoelectric generators (PEGs) and the proposed HF-PEG and FUC-PEG in this work, figures of schematics and photos of the as-fabricated iCUPE with the explosive view and the assembled view, design of the core circuit for data acquisition and power management, evaluation of the mechanical performance of the HF-PEG with different design parameters, comparison of the recognition accuracies of acceleration, frequency, and angle between the single-channel and three-channel-based sensing, 2D t-SNE maps for acceleration, frequency, and tilting angle, comparison of the recognition accuracy of acceleration and frequency under nonresonant and resonant frequencies, photo of the test setup for iCUPE, open-circuit voltage of the HF-PEG in time domain under different conditions tested by frequency up-sweep, stability test of FUC-PEH at frequencies of 214 and 31 Hz, output power performances of HF-PEGs I, II, and III at resonant frequencies of 209, 218, and 214 Hz, real-time sensing signals of the three-channel LF-PEGs in different driving scenarios, flow diagram of the iCUPE enabled intelligent monitoring system based on digital twin technique, and confusion map of the recognition of the operation status for the pump monitoring demonstration in the underground mining, and discussions of design of the core circuit of iCUPE and iCUPE enabled intelligent monitoring system based on digital twin technique (PDF)

Video of demonstration of the vehicle driving status monitoring using iCUPE (MP4)

Video of demonstration of digital-twin-based monitoring in a mine environment using iCUPE (MP4)

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Author Contributions
M.H. and M.Z. contributed equally to this work. M.H., M.Z., and C.L. conceived the idea. M.H., M.Z., and X.F. planned the experiments. M.H., T.T., X.G., and X.F. designed and completed the hardware and performed the experiments. M.H. took all the photos shown in the figures. M.Z., M.H., and Z.Z. wrote the control programs and algorithms for machine learning and demonstration. M.Z., M.H., H.L., and T.C. contributed to the data analysis and drafted the manuscript. M.H., M.Z., H.L., L.S., and C.L. edited the manuscript.

Funding
This work was supported by the Natural Science Foundation of Jiangsu Province for Distinguished Young Scholars (Grant No. BK20220056); the research grant of RIE advanced Manufacturing and Engineering (AME) programmatic grant A18A4b0055 “Nanosystems at the Edge” at NUS, Singapore; and the National Key Research and Development Program of China (Grant No. 2019YFB2004800).


(35) Liang, X.; Jiang, T.; Liu, G.; Feng, Y.; Zhang, C.; Wang, Z. L. Environmental Science Spherical Triboelectric Nanogenerator Inte-


