A high output magneto-mechano-triboelectric generator enabled by accelerated water-soluble nano-bullets for powering a wireless indoor positioning system†

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A high-performance magneto-mechano-triboelectric nanogenerator (MMTEG) was demonstrated by introducing accelerated water-soluble nano-bullet modified nanostructures to convert a gentle magnetic field into electric energy for powering an indoor wireless positioning system. NaCl salt nanoparticles were accelerated by an aerosol deposition (AD) process to collide on a perfluoroalkoxy (PFA) film with a high kinetic energy for the formation of a complicated nanomorphology on the triboelectric active surface. Under an alternating current (AC) magnetic field of 7 Oe, the MMTEG generated an open-circuit peak-to-peak voltage (Vpp) and a short-circuit current of 708 V and 277 mA, respectively. The harvesting device also presented a maximum peak power of 21.8 mW as well as a continuous AC output power of 4.8 mW (4.8 mJ per second). A self-powered indoor IoT positioning system was constructed by integrating the MMTEG, a power managing circuit, a storage element, and an IoT Bluetooth beacon. The electric energy from the MMTEG device enabled continuous operation of a beacon device, and we successfully confirmed the accurate location of the installed wireless positioning system, subsequently resulting in transmission of our indoor position to the main monitoring computer. Lastly, the MMTEG generated an open-circuit Vpp and a short-circuit current of 330 V and 23 mA, respectively, near a 60 Hz power cable connected to home appliances, which were large enough to turn on 108 blue light emitting diodes (LEDs).

Broader context
The internet of things (IoT) is a key factor for the advent of industry 4.0, which is the network of electronic devices, home appliances, and vehicles to remotely monitor and control these systems. To operate compact IoT components, batteries are widely utilized as electric power sources, and the batteries inevitably require periodic replacement owing to the limited lifetime. Various energy harvesting technologies may be alternatives to batteries inside IoT components since they can convert ambient energy into electric energy. Especially, we are always surrounded by stray alternating current (AC) magnetic fields arising from electric power cables in buildings, factories, infrastructure, power transmission lines, and cars by Ampère’s law. Magneto-mechano-electric (MME) generators have provided effective acquisition of electric power from the wasted magnetic fields. In this work, we introduce a high output MME generator by utilizing the triboelectric effect and water-soluble nano-bullet modified nanostructures to supply power to IoT systems.

Introduction
With the advent of industry 4.0, the internet of things (IoT) technology has a key role to collect information, analyse it, and create an action for realizing mutually connected automated systems related to human healthcare, environmental monitoring, industrial manufacturing, and public safety.1,2 However, the practical implementation of IoT devices such as wireless sensors, data loggers, and compact actuators in any location is severely
restricted due to the difficulty in finding proper power sources. For example, connection of external electric powering wire or embedment of lifetime-limited batteries in billions of sensor nodes would be practically impossible owing to the tremendous increment of expenses and labour effort for construction and maintenance of the systems. In this regard, a standalone-powered system with an energy harvesting device for individual IoT nodes should be exploited to actualize sustainable, maintenance-free, and independent IoT applications.

Magnetoe-mechano-electric (MME) generators have attracted a great deal of attention for developing self-powered IoT systems since MME harvesters could continuously scavenge electricity from stray alternating current (AC) magnetic fields [typically less than 1 mT (= 10 Oe) at a fixed frequency of 50/60 Hz] arising from electric power cables that are installed everywhere including buildings, factories, infrastructure, and electric power transmission systems. To date, MME devices have been mainly fabricated with composites of piezoelectric materials, magnetostrictive materials, and magnetic proof masses to initially convert a magnetic field into mechanical movement by a magnetostriction effect and magnetic force, which is subsequently transduced to electric energy by the piezoelectric effect. Recently, a piezoelectric single crystal with a high charge constant $d_{33}$ of $\sim 1800 \text{ pC N}^{-1}$ was utilized in a generator to achieve an outstanding continuous AC root mean square (RMS) output power of 4.6 mW from a MME generator under a weak AC magnetic field of 7 Oe. Nevertheless, the time consuming and costly production process for a piezoelectric crystal or textured magnetostrictive metal could be a challenging factor for expanding the utilization of these single crystal-based MME generators.

Energy harvesting systems utilizing the triboelectrification effect, called triboelectric nanogenerators, are promising candidates to substitute piezoelectric parts in MME devices since they can harvest electrical power from mechanical and vibrational energy such as wind blowing, hand touching, and engine shaking with benefits of being inexpensive, efficient, simple, and more suitable alternatives for emerging various IoT applications. The triboelectric phenomenon can be described as a charge transfer process via contact electrification between two different substances with distinct tribo-polarities. There were various attempts to combine mechanical triboelectric nanogenerators with different kinds of harvesters. Yang et al. successfully integrated a triboelectric nanogenerator and an electromagnetic generator to suggest a new hybrid-type high performance mechanical energy harvester. With the rotating-disk-based hybridized structure, the electromagnetic generator produced 8.4 mW and the triboelectric nanogenerator produced 8.6 mW. To demonstrate a magneto-mechano-triboelectric nanogenerator (MMTEG), Huang et al. fabricated a composite of PDMS and Fe–Co–Ni powder to fulfill roles of triboelectric harvesting and magnetic field responsive vibrating materials. Although the device can generate an open-circuit voltage of 325 V and a short-circuit current of 9.2 $\mu$A under an external AC magnetic field, the applied field above 1000 Oe may be excessively high for practical applications involving a weak ambient magnetic noise field.

Meanwhile, to enhance the performance of triboelectric nanogenerators, many research teams have sought to optimize the contact surface morphology. The morphological property of the contact area could exert a significant influence on frictional electrification and contact-induced charges in triboelectric devices. Several approaches for tailoring the surface topography into nanometre or micrometre scales (e.g., polymer dry-etching, surface attached nanoparticles, chemically modified nanowires, block copolymer self-assembly, inverse opal structures, anodic aluminium oxide, etc.) have previously been developed to achieve advanced triboelectrification, but most of them required a costly or toxic fabrication process with high-vacuum equipment, ultraviolet lithography, or diverse chemicals.

Herein, we demonstrated a MMTEG operating under a gentle magnetic field with truboelectric surface nanomorphology enabled by eco-friendly and water-soluble accelerated nanobullets to develop a self-powered indoor wireless positioning system. NaCl salt nanoparticles were sprayed like high-speed bullets on a perfluoroalkoxy (PFA) film by an aerosol-deposition (AD) process with a high kinetic energy to form surface nanostructures on the triboelectric active layer. The cantilever-type MMTEG assisted by NdFeB magnet proof masses was constructed with the PFA and Al foil as the triboelectric counterpart materials. Through a study of finite element analysis (FEA), we designed the device structure with consideration of the optimum resonance mode to maximize the output performance of the harvesting device. Our MMTEG can generate an open-circuit peak-to-peak voltage ($V_{pp}$) and a short-circuit current up to 708 V and 277 $\mu$A, respectively, under an AC magnetic field of 7 Oe induced from a Helmholtz coil. The device also presented a maximum peak power of 21.8 mW (peak power density of 335.4 mW cm$^{-2}$) in the volume of active triboelectric materials as well as a continuous AC output power of 4.8 mW (AC power density of 73.8 mW cm$^{-2}$) in the volume of active triboelectric materials that was calculated from integration of the output voltage waveform. The electricity of the MMTEG was directly utilized to operate a wireless indoor positioning system by integration of the energy harvester, a rectifying/converting circuit, a storage element, and an IoT Bluetooth beacon. With the MMTEG power supply, the wireless beacon can continuously operate without an external electrical source or battery, and we successfully monitored the accurate location of the installed beacon by Bluetooth communication, subsequently resulting in delivery of our indoor position to the main server computer. Finally, the MMTEG was deployed near a 60 Hz power cable of common home appliances to generate an open-circuit $V_{pp}$ of 330 V and a short-circuit current of 23 $\mu$A, which were large enough to light up 108 blue light emitting diodes (LEDs).

**Result and discussion**

**Materials and design of the MMTEG**

Fig. 1a shows a schematic illustration of the fabrication process for the nano-structured film using the accelerated NaCl nanoparticles by the AD process to increase the contact-charging...
The combination of PFA and Al foil could derive high performance triboelectric harvesting due to their negative and positive charge affinities, respectively. The schematics of Fig. 1b show the working mechanism of the MMTEG harvester utilizing the triboelectric effect and electrostatic induction with vibration of the cantilever beam under the AC magnetic field.\textsuperscript{15,51} The charge transfer does not occur in the original state before initial contact of the two triboelectric layers (Fig. 1b(i)). When the surfaces of the PFA film and Al foil are contacted by movement of the cantilever structure responding to the external magnetic field, the triboelectric charges are generated with negative polarity on the top surface of the PFA film and positive charges on the bottom surface of the Al foil, as shown in Fig. 1b(ii). The anions are provided from the more positive side in the triboelectric series to the more negative side. The positive and negative triboelectric charges still stay on the surfaces of the PFA and Al when these two surfaces are detached in a moment, thus inducing the opposite charges on the Au electrode of the PFA film (Fig. 1b(iii)). An electron flow is then generated by the difference of electric potential between the two triboelectric parts in order to satisfy overall electrical balance until a fully released state is achieved, as presented in Fig. 1b(iv). Subsequently, the upward vibration decreases the gap distance of the two triboelectric layers again, resulting in a decline of dipole moments in the gap, and the change of the electrical potential difference creates electron flow from the top Al to the bottom Au electrode to eliminate the accumulated charges (Fig. 1b(v)). Fig. 1c shows the experimental setup to measure the output performance of the MMTEG under the AC magnetic field induced by the Helmholtz coil. One end of the cantilever structure composed of a PFA film with nanomorphology, a Ti plate, and permanent magnets was clamped by a Bakelite rig-non-magnetic metal (in the inset of Fig. 1c), and the assembly was installed inside the Helmholtz coils. The Al foil was located above the vibrating cantilever part with the optimized gap distance about 1 mm to generate maximum output signal. The gap distance between PFA and Al was an important factor; as the gap distance increased, the output performance gradually increased until reaching a particular point.\textsuperscript{16} The Helmholtz coil can generate a uniform AC magnetic field around the MMTEG sample, and the magnetic field can simply be changed by control of the input AC current.\textsuperscript{52} The magnet proof mass facilitated continuous vibration of the cantilever beam by interacting attraction and repulsion with the surrounding AC magnetic field. Furthermore, it permitted tuning of the resonance frequency of the harvesting device by adjusting the number or position of magnets since the amplitude of the cantilever movement could be significantly greater in the resonance mode than in the off-resonance condition.\textsuperscript{53} Fig. 1d shows a scanning electron microscopy (SEM) image of the nano-bullet modified PFA surface with complicated nanomorphology. The nanostructures were uniformly formed on the whole area of the PFA surface, as presented in Fig. S2a (see the ESI†), and the salt nanoparticles completely vanished in the water with a water-soluble property. Comparing the image of the nano-structured PFA film to a pristine state (Fig. S3 in the ESI†), we confirmed that the NaCl powder acceleration and post water dissolving procedure successfully developed the nanomorphology.
on the target material in a simple, fast, and eco-friendly manner. The surface elemental composition was analysed after the formation of the nanomorphology by X-ray photoelectron spectroscopy (XPS), as shown in Fig. 1e. Due to the original components of PFA, numerous fluorine atoms existed on the surface of the sample, while Na and Cl constituents were not observed even in the magnified XPS surveys, as shown in Fig. S4 (see the ESI†), which also indicated the perfect elimination of salt powders from the triboelectric surface. Note that fluorine is widely known as the most electronegative element, enabling high performance triboelectric energy harvesting.54

Harvesting performance of the MMTEG

We investigated the output performance of the MMTEG in the Helmholtz coil that generated a homogeneous AC magnetic field. The entire area of the cantilever structure was $60 \times 20 \text{ mm}^2$, and the active area of the triboelectric PFA film was $50 \times 20 \text{ mm}^2$ for this measurement. The resonance frequency of the MMTEG generator was 143.2 Hz by locating 7 magnet masses (a total weight of 10.5 g) at the end of the cantilever. To verify the effect of nano-bullet induced structures on the triboelectric performance, we compared the harvesting outputs between the surface modified PFA film and non-modified control sample upon ME operation. With the AC magnetic field of 7 Oe at 143.2 Hz, open-circuit $V_{pp}$ and short-circuit current signals of MMTEG devices with and without the nanomorphology reached up to 708 V and 277 $\mu$A (see Video S1 in the ESI†) and 448 V, and 118 $\mu$A, respectively, as shown in Fig. 2a and b. The nano-bullet AD process can derive significant improvement of the output voltage and current of 58% and 235%, respectively, for the energy harvesting. We measured the electric output of the MMTEG with the nanomorphology in response to different magnetic fields from 3 Oe to 11 Oe as shown in Fig. S6 (see the ESI†). The voltage output was increased with the increment of the magnetic field and nearly saturated from the point of 9 Oe since the improvement of the output was noticeably decreased between 9 Oe ($V_{pp}$ of 722 V) and 11 Oe ($V_{pp}$ of 726 V) compared to the region of 3 to 9 Oe. To compare the output peak power of the MMTEG with and without the nanomorphology, we recorded the absolute peak voltage ($\Delta V$) with external resistances ranging from 1 k$\Omega$ to 1 G$\Omega$ for MMTEGs without nanostructures and with nanostructures. The measured absolute peak voltages under different load resistance varying from 1 k$\Omega$ to 1 G$\Omega$ for MMTEGs without nanostructures and with nanostructures. The peak powers calculated from multiplying the peak voltage and load resistance for MMTEGs without nanostructures and with nanostructures. (c) The results of the operation stability test during 35 million vibration cycles of the nano-bullet modified MMTEG.

Fig. 2 (a) The open-circuit voltage values from the MMTEG devices without nanostructures and with nanostructures. (b) The short-circuit current values from the MMTEG devices without nanostructures and with nanostructures. (c) The measured absolute peak voltages under different load resistance varying from 1 k$\Omega$ to 1 G$\Omega$ for MMTEGs without nanostructures and with nanostructures. (d) The peak powers calculated from multiplying the peak voltage and load resistance for MMTEGs without nanostructures and with nanostructures. (e) The results of the operation stability test during 35 million vibration cycles of the nano-bullet modified MMTEG.

\[ P = \frac{V^2}{R}, \] where $P$ is the power, $V$ is the output voltage, and $R$ is the resistance. As a result, the maximum peak power of the nano-bullet modified MMTEG was 21.8 mW at a resistance of 2 M$\Omega$, which was 5.7 times higher compared to the flat PFA device with a maximum peak power of 3.8 mW at 3 M$\Omega$. This noticeable enhancement in the output power of the nano-structured MMTEG could be rationalized as follows: The AD nano-bullet processed surface with rough morphology could be anticipated to give rise to a larger triboelectric contact area and stronger friction between two phases, which could result in more surface charges than the non-patterned surface.42 Moreover, the MMTEG device can generate a continuous AC output power of 4.8 mW (4.8 mJ per 1 second, the power was calculated by integrating the AC output waveform from the energy generator, Fig. S8 in the ESI†) which is larger than a recently reported piezoelectric single crystal-based MME harvester.9 In many cases among previously reported triboelectric nanogenerators, the harvesting operation is discontinuous or impulsive, thus the generated electric power from the triboelectric nanogenerators might be small.15 To the contrary, since our MMTEG was operated in resonance mode, the out power signal was similar to the one from a piezoelectric resonance mode generator (i.e., sinusoidal wave output), thus the generated continuous power could be much larger than that from other triboelectric generators. The output stability and mechanical durability are important features of the energy generator.55,56 To evaluate the fatigue property of the MMTEG, an elastomer polydimethylsiloxane (PDMS) with a thickness of ~50 $\mu$m was coated on the backside of the Al foil (counterpart triboelectric layer against the PFA film) to mechanically support the thin metal layer, and then the maximum output $V_{pp}$ was recorded during 35 million cycles under an AC magnetic field with 7 Oe and 143.2 Hz as presented in Fig. 2e. Note that, without the PDMS layer, cracks easily occurred at the Al foil in the durability test, and the MMTEG did not maintain its original output performance. The insets of
Fig. 2e show the time-dependent $V_{pp}$ graphs at the initial state (685 V), 1 million cycles (672 V), and 33 million cycles (651 V). We observed an electric output fluctuation of less than 5% during 33 million cycles. As a result, we confirmed that the MMTEG generator had remarkable durability during 33 million cycles, which was outstanding compared to other triboelectric nanogenerators including even a non-contact type.⁵⁷–⁶¹ The stability performance of our MMTEG may be increased with further optimization of the device structure and friction materials for practical applications of self-powered electronic systems.

**Working mechanisms of the MMTEG**

To elucidate the working mechanisms of the cantilever-type MMTEG, we conducted theoretical simulations to analyse the mechanical resonance mode as well as the generated triboelectric potential by utilizing a FEA program. First, the eigenfrequency modes of the harvesting device were classified to verify the deformation shapes of the rectangular beam at resonance frequencies. For the analysis, one end of the cantilever was clamped and mass magnets were located at the opposite tip area. Even though there would be various resonance modes including bending, torsional, and axial modes for the cantilever-type devices, bending modes might be the most suitable for our MMTEG application since they can offer up and down motions to orthogonally bump each triboelectric layer effectively.⁶² For the first harmonic bending mode, the tip mass of the MMTEG had the largest displacement of vibration movement as the typical cantilever motion, which was manifested at a resonance frequency of 15.1 Hz with an output open-circuit $V_{pp}$ of 149 V under an AC magnetic field of 7 Oe in the real experiment as presented in Fig. S9 (see the ESI†). While for the second harmonic bending mode, the middle area of the triboelectric cantilever had the largest displacement of vibration movement as shown in Fig. 3a, which was revealed at a resonance frequency of 143.2 Hz with an output open-circuit $V_{pp}$ of 708 V in the real test (Fig. 2a). The performance difference between the first and second bending eigenfrequency modes of the MMTEG may be explained by the triboelectric contact area of the PFA film and Al foil. The second harmonic bending mode could provide a larger active triboelectrification area in the harvesting operation compared to the first harmonic bending mode, thus resulting in a noticeable improvement of the voltage output. For this reason, we finally adopted the second bending resonance mode for the MME triboelectric device. Second, to verify the effect of nanostructures on PFA on the triboelectric potential, we examined the theoretical equations and then carried out an analytical simulation compared to the normal flat PFA surface. The theoretical voltage generation from the contact-mode triboelectric generators is defined by the following eqn (1).⁶³

$$V = -(Q/S\varepsilon_0)(d/e + x) + \sigma x/\varepsilon_0$$  

(1)

where $V$ is the difference potential between two electrodes, $Q$ is the transfer charge in between two layers, $S$ is the area size of the electrode, $\varepsilon$ is the permittivity of the PFA film, $\varepsilon_0$ is the permittivity of free space ($8.85 \times 10^{-12}$ farad m$^{-1}$), $d$ is the thickness of the PFA film, $x$ is the separation distance between the Al foil and the PFA film, and $\sigma$ is the triboelectric charge density. At the open-circuit condition, there is no charge transfer ($Q = 0$), and the open-circuit voltage ($V_{oc}$) is expressed by eqn (2) below.⁶⁴

$$V_{oc} = \frac{\sigma x}{\varepsilon_0}$$  

(2)

From this equation, we obtained a maximum triboelectric charge density $\sigma$ of 0.69 $\mu$C m$^{-2}$ on the flat PFA surface in the open-circuit state by employing a maximum $V_{oc}$ of 233 V (Fig. 2a) and a maximum distance $x$ of 3 mm (Fig. S10 in the ESI†) between PFA and Al in real measurements. Subsequently, we compared the calculated triboelectric potentials, as shown in Fig. 3b, between the nano-patterned geometry and non-patterned flat layer in the simulation program with an input of the triboelectric charge density $\sigma$ of 0.69 $\mu$C m$^{-2}$ and distance $x$ of 3 mm. The triboelectric output voltage was proportionally enhanced with the larger contact area since it could cause a higher amount of total charges on the electrified surfaces.⁴²,⁶⁵ The FEA result indicated that the increase of surface area with nano-bullet modified structures could produce a higher electrical potential in the MMTEG compared with a flat triboelectric layer that had the same device structure and size.

**Demonstration of a self-powered indoor positioning system**

Fig. 4a shows an application concept of powering a wireless indoor positioning system by utilizing the MMTEG. (i) The triboelectric device can generate electric energy under an AC magnetic field to activate an IoT positioning beacon. (ii) When a user approaches near to the target beacon, the IoT device can transmit a wireless signal of its location information to a handheld smart pad by the Bluetooth low energy (BLE) protocol. (iii) The accurate position of the person is sent from the portable smart pad to the main monitoring computer through wireless internet service. This type of system offers not only a demonstration of a self-powered IoT beacon to find the accurate
location of a target object but also simultaneous monitoring of personal position in an indoor environment. We designed the self-powered IoT positioning system including the MMTEG, power managing circuit (composition of a voltage regulating 0.1 mF capacitor \(C_1\) and Linear technology LTC3588 circuit), storage capacitor \((C_2, \ 1 \ \text{mF})\), and IoT positioning beacon (Vintech Wezon) as shown in Fig. 4b. Note that, even though the LTC3588 is widely known as a low-power consumption circuit with a role of energy conversion, it is not designed for our MMTEG which has a high internal impedance and generates a very high output \(V_{pp}\) up to 708 V and relatively low output current up to 277 \(\mu\)A. For these reasons, the energy conversion process of the MMTEG could cause a huge energy loss.\(^{66}\) The AC-type high output voltage of the triboelectric nanogenerator was not appropriate for commercial electronics usually operating under a direct current (DC) voltage of 5 V.\(^{66}\) To solve this problem, the AC output of the MMTEG was rectified and converted into a constant DC voltage of 3.6 V to charge a storage capacitor \(C_2\) via the power managing circuit. After operation of the MMTEG under an AC magnetic field of 7 Oe, the 1 mF capacitor was charged from 0 V to 3.6 V within 158 seconds, and then the IoT beacon was connected to the capacitor, as presented in Fig. 4c. When the beacon device was turned on, the voltage in the capacitor dropped to 2.8 V to induce the initial wake-up of the internal electronic circuit, and subsequently the charged voltage was slightly recovered up to 3.5 V by the electric energy generated from the MMTEG generator. The inset of Fig. 4c shows that the beacon device can continuously transmit the positioning signal with an interval of 1 second as a self-powered IoT system. Fig. 4d shows captured images of the monitoring program on the smart pad with the corresponding physical distance between the positioning beacon and the user. (i) The user is situated very far from the IoT beacon installed in room #1. The program presented the state of ‘No Signal’. (ii) When the user approached the door of room #1, the program displayed the state of ‘Far State’ since the signal from the IoT beacon was weak due to the obstacle. (iii) After the user entered room #1, the program indicated the state of ‘Near State’ which meant that the self-powered positioning beacon system was very closed to the smart pad. Finally, in the ‘Near State’, the positioning information of the user was delivered to the main monitoring computer from the smart pad via wireless internet (Fig. S13 in the ESI†). The whole procedure of wireless indoor positioning was recorded in Video S2 (see the ESI†). This demonstration verified that our MMTEG could continuously supply sufficient electric power to the IoT system without an external power source or internal battery.

**Energy harvesting of the MMTEG near an ambient power cable**

We also confirmed the possibility of MMTEG harvesting under a 60 Hz stray magnetic field around an electric power cable connected to home appliances. For the experiment, the size of the cantilever Ti substrate of the MMTEG was changed to \(95 \times 20 \times 0.3 \ \text{mm}^3\) with an active triboelectric area of \(50 \times 20 \ \text{mm}^2\), and 12 magnet masses (a total weight of 18 g) were attached at the end of the cantilever beam in order to tune the device resonance frequency to 60 Hz. The increased mass weight compared to the MMTEG device in Fig. 2 could increase the movement distance of the cantilever during operation, which may derive a high output. Fig. 5a shows the experimental setup composed of the MMTEG, an electric power cable of hairdryers, and an oscilloscope. The power cable was placed under the tip mass of the triboelectric cantilever with a distance of 1 mm to derive a strong response between the magnets and a magnetic field without blocking the magneto-mechano vibrations. Fig. 5b shows that the measured RMS AC current in the power cable was 9.2 A by operation of two hair dryers. By using Ampère’s law, we calculated an AC magnetic field of \(\sim 1.3 \ \text{Oe}\) applied on the centre point of the mass magnets located at the end part of the cantilever structure (a total distance of 14 mm between the core of the electric cable and the centre point of the mass magnets, Fig. S14 in the ESI†). The harvesting device generated a 60 Hz open-circuit \(V_{pp}\) of 330 V and a short-circuit current of 23 \(\mu\)A, as shown in Fig. 5c and d, respectively (Video S3 in the ESI†). With operation of one hair dryer, the power cable transmitted a RMS AC current of 5.0 A (corresponding to an AC magnetic field of \(\sim 0.7 \ \text{Oe}\) at the middle layer of the magnet stack), and the
output $V_{pp}$ and current signals of the MMTEG device reached 151 V and 11.7 $\mu$A, respectively, as presented in Fig. S15 (see the ESI†). Fig. 5e shows that the rectified output of the MMTEG near the electric power cable can be directly utilized to light up 108 blue LEDs continuously (Video S4 in the ESI†).

Conclusions

In summary, we report a high performance MMTEG based on nano-bullet modified structures to power an indoor wireless positioning system. Water-soluble NaCl salt nanoparticles were utilized to form a nanomorphology on the triboelectric PFA film by high-kinetic AD and a subsequent eco-friendly dissolution process. The MMTEG device adopted the optimum resonance mode and device structure derived from the FE analysis to maximize the triboelectric performance. With a gentle AC magnetic field of 7 Oe, our MMTEG can generate an open-circuit $V_{pp}$ of 708 V and a short-circuit current of 277 $\mu$A. Furthermore, we also achieved a maximum peak power of 21.8 mW and a continuous AC output power of 4.8 mW from the triboelectric device at an external resistance of 2 M$\Omega$. The high-outputs of the MMTEG originated from the large surface area modified by the nano-bullet AD process and vibration motions with the second bending resonance mode, which led to enhancements of contact tribo-electrification and electrostatic induction with extraordinary endurance up to 33 million vibration cycles. By rectifying and converting electric power from the MMTEG, we demonstrated a continuously operating self-powered wireless indoor positioning system consisting of a magnetic field harvester, power control circuit, storage element, and IoT Bluetooth beacon. Lastly, the MMTEG device was introduced near a 60 Hz power cable connected to home appliances to generate an output open-circuit $V_{pp}$ of 330 V and a short-circuit current of 23 $\mu$A, which were large enough to turn on 108 blue LEDs. These results verify the feasibility of our MMTEG for not only operating self-powered IoT electronics but also harvesting electric energy from a stray weak magnetic field to realize specific self-powered applications including smart factories, structural/environmental monitoring, and living intelligent systems.1,67 Moreover, the MMTEG may be further combined with various harvesters operated by electromagnetic, wind, solar, thermal, or chemical energy to increase the total electric output of the harvesting system.27,31,68

Experimental

Preparation of the nanomorphology of the PFA film

Edible NaCl salt mixed with ethanol and zirconia balls was ground by planetary milling at 150 rpm for 3 hours. After finishing the planetary milling, the salt solution was dried at 80 °C for 1 hour to evaporate the ethanol. The agglomerative salt powder lumps were crushed in a mortar to form fine particles. For the AD process, the mixture of salt nanoparticles and carrier gas (a flow rate of 28 L min$^{-1}$) was transported through a tube to a nozzle, and ejected from a rectangular-shape nozzle (a slit size of 35 $\times$ 0.5 mm$^{2}$) to collide on a PFA film in a deposition chamber with a base vacuum pressure of 0.5 Torr at room temperature. The deposition time for fabrication of the nano-structured PFA film was ~16 seconds, since the horizontal moving speed of the sample holder was 3.1 mm s$^{-1}$ and the length of the PFA film was 50 mm. In order to remove the salt particles, the PFA film was dipped in a sonication water bath at 60 °C for 1 hour. After drying the PFA film in an oven at 80 °C for 10 minutes, an Au electrode layer was deposited on the backside of the PFA films using a sputtering system.

Simulation of resonance modes and triboelectric potential

The theoretical simulation was conducted using the COMSOL Multiphysics program. For the calculation, we input the mechanical parameters (Young’s modulus, density, and Poisson’s ratio) of Ti, the NdFeB magnet, and PFA, as shown in the table below.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young’s modulus (GPa)</th>
<th>Density (kgm$^{-3}$)</th>
<th>Poisson’s ratio</th>
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Measurement of the electric output of the MMTEG

The Helmholtz coil is a single axis type composed of copper wire (a diameter of 1.4 mm) turns and a Bakelite frame. The inner
diameter and the distance between coil pairs in the Helmholtz coil are 62.5 and 125 mm, and a uniform magnetic field is produced in the range of ±22.5 mm at the centre point along the axis of the Helmholtz coil. The resistance and inductance of the coil are 1.07 Ω and 1.5 mH, respectively. The Helmholtz coil was designed to generate a magnetic field of 6 Oe through an input AC current of ~1 A, and we applied an AC current of ~1.2 A to the Helmholtz coil to generate 7 Oe at the centre area of the coil. The output voltage and current of the MMTEG under the AC magnetic field were measured by a digital oscilloscope (WaveSurfer 44MXs-A, Teledyne LeCroy) and a sourcemeter (2611A, Keithley), respectively.

Conflicts of interest
There are no conflicts to declare.

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Notes and references