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Shitong Fang,^{1,2} Yi Guan,^{1,2} Jiabao Zou,^{1,2} Miao Chen,³ Liangdong Wei,³ Liuchao Jin,⁴ Zhihui Lai,^{1,2} Biao Wang,⁵ Mingjing Cai,^{3,a)} and Wei-Hsin Liao^{4,b)}

AFFILIATIONS

¹National Key Laboratory of Green and Long-Life Road Engineering in Extreme Environment (Shenzhen), Shenzhen University, Shenzhen 518051, China

²College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen 518051, China

³Guangzhou Institute of Technology and School of Mechano-Electronic Engineering, Xidian University, Guangzhou, China

⁴Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China

⁵Department of Medical Ultrasound, National Clinical Research Center for Geriatrics, West China Hospital, Sichuan University, Chengdu 610041, China

^{a)}Author to whom correspondence should be addressed: caimingjing@xidian.edu.cn

^{b)}Electronic mail: whliao@cuhk.edu.hk

ABSTRACT

Self-powered monitoring of slowly rotating components is hindered by the small relative speed and limited installation space available to conventional rotary triboelectric nanogenerators (TENGs). Here, a continuously driven unidirectional rotary TENG (CDUR-TENG) is developed by integrating a multilayer spiral-spring electrode with a ratchet-triggered energy-storage/release mechanism. During winding, the spring stores elastic energy while its adjacent triboelectric interfaces progressively separate; ratchet disengagement then initiates rapid elastic recoil and concentrated charge transfer. The device therefore decouples the electrical pulse from the slow external rotation. At 0.2 Hz, the CDUR-TENG provides a peak-to-peak open-circuit voltage of approximately 130 V and a maximum short-circuit current of 55 μA ; it transfers 0.165 μC per cycle and reaches a maximum instantaneous power of 2.182 mW at 1 Hz and 1.1 M Ω . The resulting normalized power density reaches 191.4 W m⁻³Hz⁻¹, at least 8.57 times that of the compared rotary harvesters. Voltage signatures further distinguish operating angle, angular overshoot, and reverse rotation, demonstrating a compact route toward self-powered condition monitoring under ultra-low-frequency rotation.

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Low-frequency rotational motions are widespread in intermittently operated mechanical systems, yet they are difficult to exploit for self-powered monitoring because the available displacement rate is small and the installation envelope is often constrained. Triboelectric nanogenerators (TENGs)^{1–3} are attractive for such applications because they are lightweight, material-flexible, and can directly generate electrical signals from contact electrification and electrostatic induction. Existing electromagnetic, piezoelectric, thermoelectric, and triboelectric harvesters have enabled many forms of distributed sensing;^{4,5} however, the performance of rotary devices remains particularly sensitive to the available relative motion and the effective interfacial area.^{6–23} The

potential applications of the continuously driven unidirectional rotary (CDUR)-TENG in low-frequency rotational energy harvesting and self-powered condition monitoring are illustrated in Fig. 1.

Rotary TENGs generally employ either sliding or contact-separation interfaces. Sliding-mode designs can provide a large nominal friction area, but they require sustained relative sliding speed and may occupy a larger swept volume than their static package suggests.^{24–29} Contact-separation designs can generate strong voltage pulses at low frequency, but their active area and the requirement for bidirectional reciprocating motion limit their use in compact unidirectional drives.^{30,31} The essential challenge is therefore to increase the effective



FIG. 1. Conceptual applications of the CDUR-TENG for compact, self-powered monitoring of low-frequency rotating equipment.

triboelectric interface and create a rapid internal charge-transfer event without demanding rapid external rotation.

Here, a continuously driven unidirectional rotary TENG (CDUR-TENG) is constructed from a multilayer spiral-spring electrode and a ratchet-triggered release mechanism. The spiral spring converts slow rotation into both progressive interlayer separation and stored elastic energy, whereas the ratchet periodically releases the stored energy to restore the spring rapidly. This architecture uses the same spiral component as the compliant mechanical element and the triboelectric electrode, thereby coupling

energy storage, motion conversion, and charge generation within a compact volume.

The design extends the active triboelectric interface through the thickness of the spiral rather than relying on a single planar surface. Its key benefit is not merely a larger area: rapid recoil after ratchet release concentrates the charge-transfer process into a short interval, reducing the dependence of the voltage peak on the tested external frequency. The following measurements establish the structural mechanism, electrical response, charging capability, and rotation-state sensing performance of the device.

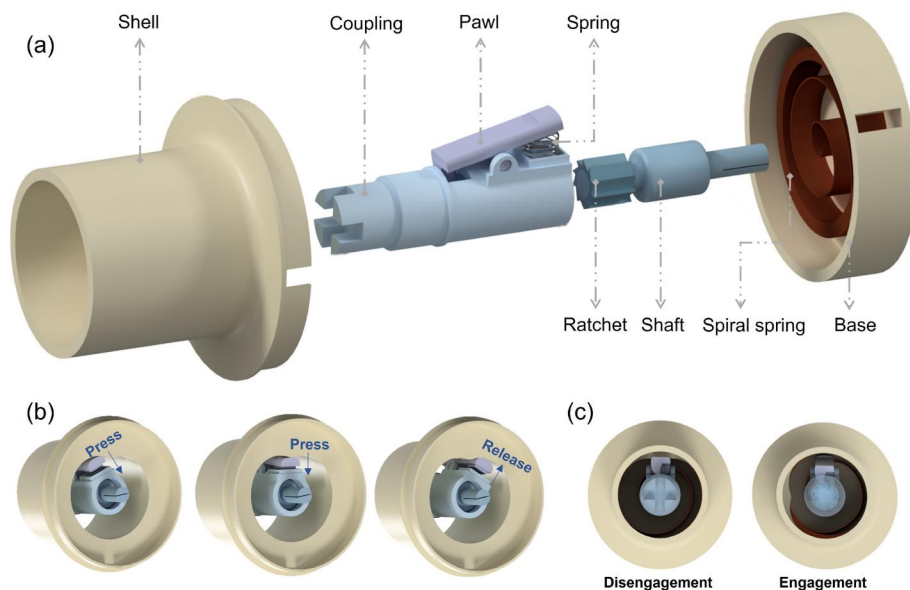


FIG. 2. Configuration and operating principle of the CDUR-TENG. (a) Exploded view of the shell, coupling, pawl, spring, shaft, and spiral-spring electrode. (b) Winding and release sequence under applied unidirectional torque. (c) Ratchet disengagement and re-engagement.

Figure 2(a) shows the CDUR-TENG assembly, which comprises a protective shell, a ratchet transmission, and a multilayer spiral-spring electrode. The shell fixes the outer end of the spring and houses the coupling and ratchet, while the alignment shaft connects the central end of the spring to the transmission. This coaxial arrangement maintains concentric winding and constrains the spiral within a compact enclosure. The structural roles are deliberately separated: the shell provides support and packaging, the ratchet controls the release event, and the spiral spring supplies both compliance and the triboelectric interfaces.

The transmission consists of a coupling, ratchet wheel, pawl, restoring spring, and alignment shaft. During normal winding, the pawl engages the ratchet and drives the spring through the shaft. A local protrusion inside the housing lifts the pawl once per coupling revolution. The pawl then disengages momentarily, allowing the stored elastic energy of the spiral spring to be released. After the protrusion is passed, the pawl reengages under the restoring force of the small spring, preparing the next winding–release cycle.

The spiral spring is consequently a dual-function element. Under applied torque, it contracts inward and stores elastic energy, while the relative displacement and separation of neighboring layers create a changing electrostatic field. Following ratchet release, rapid elastic recovery restores interlayer contact and drives the reverse charge flow. A single compact component thus replaces the otherwise separate functions of a compliant energy-storage element, a motion-conversion element, and a multilayer TENG electrode.

The operating sequence is illustrated in Figs. 2(b) and 2(c). As unidirectional torque rotates the coupling, the engaged pawl winds the spiral spring and the adjacent layers progressively separate. When the pawl encounters the housing protrusion, it is displaced out of engagement and the loaded spring recoils rapidly. This recoil simultaneously returns the layers toward contact and produces a fast electrical transient. Re-engagement then resumes winding without requiring external reverse rotation. The device therefore transforms one slow, unidirectional revolution into a gradual charge-transfer stage followed by a mechanically triggered fast-release stage.

The ratchet also provides a distinctive response to reverse motion. When the coupling is driven backward, the compliant pawl follows the ratchet profile rather than imposing a rigidly jammed constraint, as observed in Movie S1. This behavior both protects the transmission and produces a signal that is distinguishable from the waveform associated with a complete forward winding–release event.

Each spiral layer contains a stainless-steel spring substrate, Cu electrodes, and polytetrafluoroethylene (PTFE) dielectric films [Figs. 3(a) and 3(c)]. Cu and PTFE tapes are attached to the opposite sides of the steel substrate and laminated to form inner and outer electrode/dielectric surfaces. In the relaxed configuration, adjacent PTFE and Cu surfaces are in close contact. Winding increases their separation and introduces limited relative displacement, whereas release restores contact. The multilayer arrangement creates many parallel active interfaces within the radial thickness of the spring.

In the contact state, triboelectric charges are generated at the Cu–PTFE interfaces. With increasing interlayer separation, electrostatic induction drives electrons through the external circuit from the outer Cu electrode toward the inner electrode. Because the negative charges remain localized on the PTFE surfaces, separation increases the effective field across each active interface. The multilayer geometry therefore combines repeated interfacial charge generation with a

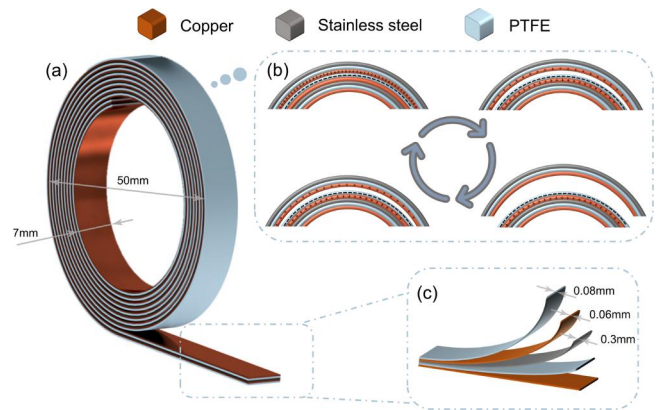


FIG. 3. Spiral-spring electrode and charge-transfer mechanism. (a) Multilayer spiral electrode. (b) Contact, separation, and return-contact states governing charge transfer. (c) Layered stainless-steel/Cu/PTFE construction.

series of spatially distributed separation gaps, rather than relying on a single macroscopic contact pair.

Upon ratchet-triggered release, the spring rapidly returns toward its original configuration. The dielectric and outer electrode re-contact, and electrons flow back from the inner to the outer electrode. The winding and recoil portions of a cycle therefore generate opposite charge-transfer directions and an alternating electrical output.

Finite-element analysis was used to resolve the deformation responsible for the electrical response. Figure 4(a) shows that increasing central rotation contracts the spiral inward and progressively opens gaps between neighboring layers. The outer turns move inward more rapidly than the inner turns, but the simulated surfaces remain separated rather than intersecting. The stress field is concentrated in

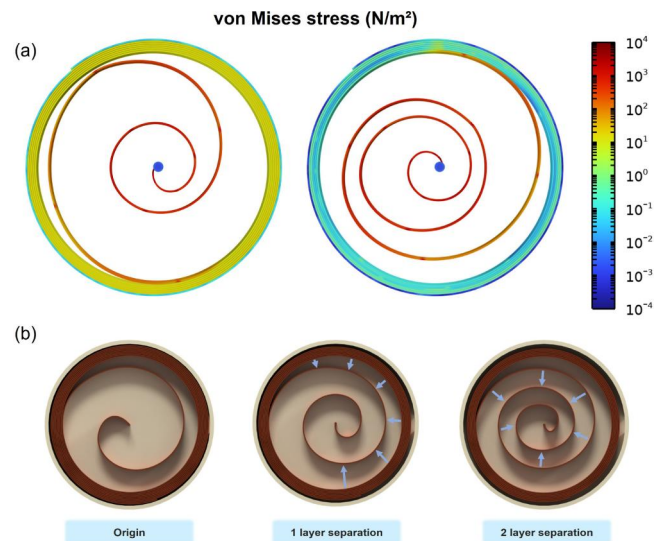


FIG. 4. Mechanical response of the spiral-spring electrode. (a) COMSOL deformation and von Mises stress fields under increasing central rotation. (b) Representative configurations at the initial state and at the one- and two-layer separation.

the central region and decays toward the outer turns, consistent with the constraint imposed by the fixed outer end and the applied central rotation. The observed prototype deformation follows the same trend (Movie S2).

The configurations in Fig. 4(b) further show that the number of separated interfaces increases nonlinearly with applied torque. The base supplies the initial constraint, whereas the central shaft converts the input rotation into progressively larger radial contraction. These results support the mechanical picture used to interpret the gradual rise of the electrical waveform before the abrupt release event.

At 0.2 Hz, the waveform in Fig. 5(a) resolves the internal stages of one cycle. The initial, gradual voltage increase corresponds to progressive torsional deformation and sequential opening of the inter-layer interfaces. As the torque rises, the deformation reaches a state in which several neighboring layers separate more synchronously, producing a steeper voltage rise. The waveform thus contains information about both the continuous winding of the spring and the changing distribution of its separation gaps.

The final sharp pulse is generated when ratchet disengagement permits rapid elastic recoil. During this short event, the previously separated interfaces return toward contact and the induced charges redistribute quickly between the Cu electrodes. The simulated configurations inserted in Fig. 5(a) reproduce the transition from gradual contraction to more synchronous separation, supporting this assignment. Importantly, the sharp output event is created by the internal release mechanism; it is not produced by a sudden increase in the externally imposed rotation speed.

This mechanically triggered response explains why useful output is retained across the tested ultra-low-frequency range. The mechanism should be described as reducing, rather than eliminating,

frequency dependence: the present data establish stable operation from 0.2 to 1 Hz. A rapid recovery is produced once per full forward rotation, enabling a pronounced current pulse even when the preceding winding process is slow.

Figures 5(b) and 5(c) compare the short-circuit current and open-circuit voltage at 0.2, 0.5, and 1 Hz. The peak current remains above $50 \mu\text{A}$, and the peak-to-peak voltage remains close to 130 V over this range. Frequency mainly changes the temporal spacing and detailed shape of the waveform: at 0.2 Hz, the gradual separation stage is readily resolved, whereas at higher frequencies the output increasingly resembles a contact-separation-dominated pulse. The preservation of voltage amplitude is consistent with recoil-controlled charge transfer.

The transferred charge is approximately $0.165 \mu\text{C}$ per cycle [Fig. 5(d)]. For an active spring area of about $7 \times 250 \text{ mm}^2$, this corresponds to a charge density of $94.3 \mu\text{C m}^{-2}$. The value reflects the use of the spring thickness to accommodate multiple active interfaces while retaining a compact radial footprint. Under a $1.1 \text{ M}\Omega$ load, the output voltage reaches at least 50 V [Fig. 5(e)], demonstrating that the rapid-release pulse can drive a practical high-impedance load.

The load-dependence in Fig. 5(f) shows that the output voltage increases with increasing load resistance, with a more pronounced rise in the high-resistance region. Meanwhile, the instantaneous power first increases and then decreases, reaching a maximum value of 2.182 mW at approximately $1.1 \text{ M}\Omega$ under 1 Hz rotation. The power maximum results from the balance between the device impedance and the external load. Reporting the load-dependent voltage and power together provides a more complete characterization of the impedance-matching behavior of the device.

The performance data also clarify the physical advantage of the spiral-spring architecture. The output is not attributed only to a larger

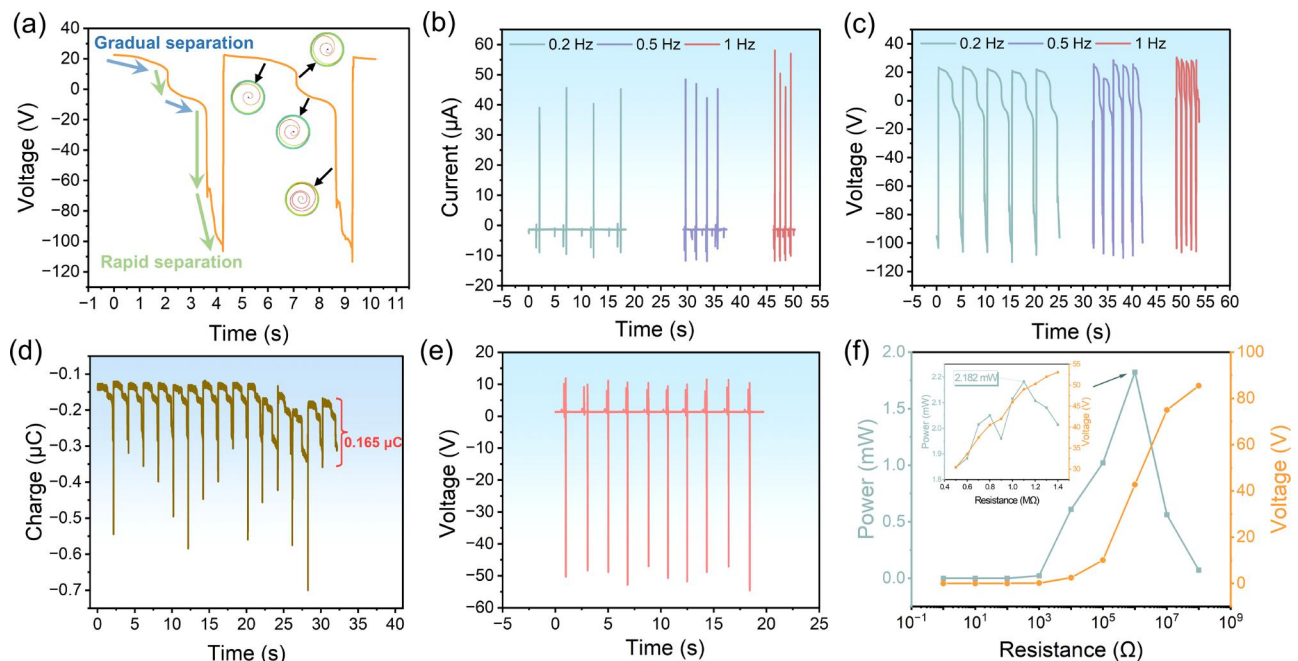


FIG. 5. Electrical characteristics of the CDUR-TENG. (a) Open-circuit voltage during a 0.2 Hz cycle. (b) Short-circuit current and (c) open-circuit voltage at 0.2, 0.5, and 1 Hz. (d) Transferred charge per cycle. (e) Load voltage at $1.1 \text{ M}\Omega$. (f) Load-dependent output voltage and instantaneous power.

geometric area; the coupled effects of multilayer interfaces, elastic energy storage, and fast release provide a larger effective charge-transfer rate at the instant of recoil. This combination is particularly useful when the ambient rotation is too slow to sustain a conventional sliding interface.

The CDUR-TENG was next evaluated as a rotation-state sensor. In Fig. 6(a), repeated operation within three angular ranges produces periodic signals with distinct amplitudes. As the rotation angle increases beyond the normal range, the amplitude changes abruptly when the device passes a full revolution and the spiral spring releases its stored energy. This angular-overshoot signature arises from the change in spring configuration and demonstrates that the output waveform can provide more than a simple rotation count.

Figure 6(b) shows the response to a sudden reversal. During normal forward operation, the waveform follows the same winding-release pattern described earlier. When rotation reverses, the spiral electrode returns toward its initial state before completing the forward cycle, and the resulting voltage amplitude is markedly lower than that associated with angular overshoot. The high input impedance of the measurement circuit also makes the subsequent charge redistribution comparatively slow. Accordingly, a reversal and a stopped state can be differentiated from a completed forward release by their characteristic amplitude and decay behavior (Movie S3).

The device also charges capacitors at a low excitation frequency of 1 Hz [Fig. 6(e)]. After 100 s of operation period, 100, 220, 470 nF, 4.7, and 10 μ F capacitors reach 70.2, 66.7, 46.5, 10.1, and 5 V, respectively. It should be noted that the driving frequency mainly affects the number of mechanical cycles per unit time: lower frequencies lead to a slower charging process in real time, while the energy harvested per

cycle remains comparable. Thus, the charging curve at 1 Hz can reasonably reflect the capacitor-charging capability of the device within the studied low-frequency regime. The angle-voltage map in Fig. 6(f) shows a pronounced increase in output above approximately 90°, with the principal sensing range extending to 360°. The photographs in Figs. 6(c) and 6(d) emphasize the compact, serviceable construction needed for integration with rotating equipment.

Because peak power depends on excitation frequency and device volume, the normalized power density (NPD) is used for comparison— $NPD = P/(fV)$, where P is the output power, f is the excitation frequency, and V is the total packaged volume.

Using the total device volume, the CDUR-TENG reaches an NPD of $191.4 \text{ W m}^{-3} \text{ Hz}^{-1}$ (Fig. 7), which is at least 8.57 times higher than the compared piezoelectric^{32–37} and triboelectric^{38–43} rotary devices. The comparison should be interpreted together with the design mechanism: the multilayer spiral increases the available active interfaces, while the ratchet release concentrates the output into a rapid contact-separation event. These two features enable a high power density even though the external rotation lies in the ultra-low-frequency regime. The data do not imply that every rotary application will deliver the same value; performance will depend on the available torque, rotation amplitude, package volume, interfacial durability, and electrical load.

Future optimization can increase the number and uniformity of active interfaces, reduce parasitic mechanical losses, and explore frequency multiplication or multi-release strategies. Such improvements could increase the number of useful electrical pulses per input revolution while retaining the present device's compact unidirectional operating mode.

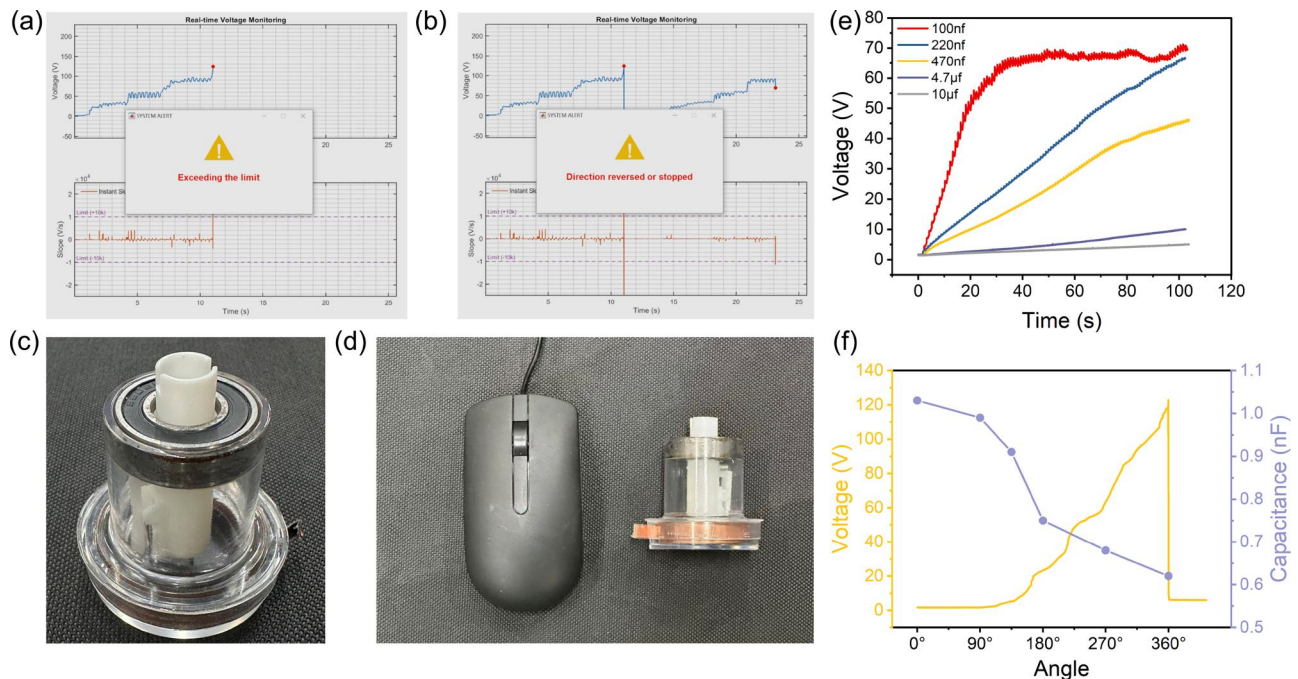


FIG. 6. Self-powered monitoring and energy-storage demonstrations. (a) Signal evolution during angular overshoot. (b) Signal response to sudden reversal. (c) Photograph of the prototype. (d) Size comparison with a computer mouse. (e) Charging curves of selected capacitors at 1 Hz. (f) Voltage amplitude and capacitance as functions of operating angle.

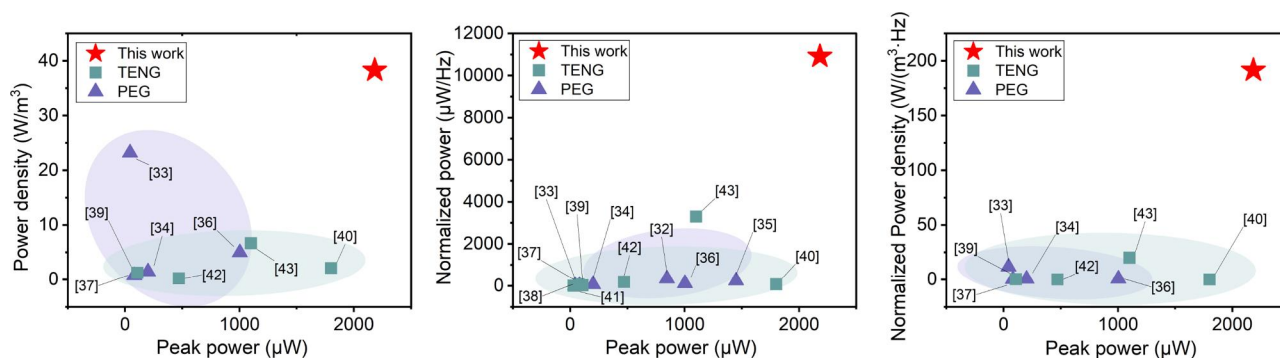


FIG. 7. Comparison of the CDUR-TENG with reported rotary piezoelectric^{32–37} and triboelectric^{38–43} energy harvesters in terms of output and normalized power density.

In summary, the CDUR-TENG integrates a multilayer spiral-spring electrode with a ratchet-controlled energy-storage/release mechanism for ultra-low-frequency rotational energy harvesting. The spiral element provides the deformable triboelectric interfaces and stores elastic energy during winding; ratchet disengagement then drives rapid recoil and concentrated charge transfer. Finite-element results and prototype observations confirm progressive inward contraction and interlayer opening under central rotation. At 0.2 Hz, the device produces approximately 130 V peak-to-peak voltage and 55 μ A short-circuit current, and it transfers 0.165 μ C per cycle. A maximum instantaneous power of 2.182 mW is obtained at 1 Hz under a 1.1 M Ω load, and the NPD reaches 191.4 W m⁻³ Hz⁻¹.

Beyond energy harvesting, the measured waveforms encode rotation state: the device identifies operating-angle changes, angular overshoot, and sudden reverse rotation, while also charging capacitors under 1 Hz excitation. The combined harvesting and sensing functions arise from a mechanically interpretable transformation of slow rotation into a fast internal release event. This approach provides a compact platform for self-powered monitoring of slowly rotating machinery, provided that the torque and angular range of the target application are compatible with the winding-release cycle.

See the [supplementary material](#) for the study of a continuously driven unidirectional rotary triboelectric nanogenerator (CDUR-TENG). It provides [Figs. 1–7](#) with their captions and alternative text, together with captions and descriptions for Movies S1–S3 on the ratchet transmission, spiral-spring deformation and recovery, and rotation-state monitoring. Figure and movie numbering follows the main article.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Shitong Fang: Conceptualization (equal); Funding acquisition (equal); Validation (equal); Writing – original draft (equal). **Yi Guan:** Data curation (equal); Investigation (equal); Methodology (equal). **Jiabao Zou:** Data curation (equal); Methodology (equal); Validation (equal). **Miao Chen:** Formal analysis (equal); Validation (equal). **Liangdong Wei:** Formal analysis (equal); Methodology (equal). **Liuchao Jin:** Data curation (equal); Validation (equal); Writing – review & editing (equal). **Zhihui Lai:** Validation (equal); Writing – review & editing (equal). **Biao Wang:** Data curation (equal); Funding acquisition (equal); Writing – review & editing (equal). **Mingjing Cai:** Conceptualization (equal); Funding acquisition (equal); Writing – review & editing (equal). **Wei-Hsin Liao:** Conceptualization (equal); Funding acquisition (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its [supplementary material](#).

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