A facile frequency tuning strategy to realize vibration-based hybridized piezoelectric-triboelectric nanogenerators

Long Liu¹,²,³ | Qiongfeng Shi¹,²,³ | Xinge Guo¹,²,³ | Zixuan Zhang¹,²,³ | Chengkuo Lee¹,²,³,⁴

¹Department of Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore
²NUS Suzhou Research Institute (NUSRI), Suzhou Industrial Park, Suzhou, P. R. China
³Center for Intelligent Sensors and MEMS, National University of Singapore, Singapore, Singapore
⁴NUS Graduate School - Integrative Sciences and Engineering Programme (ISEP), National University of Singapore, Singapore, Singapore

Correspondence
Chengkuo Lee, Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576, Singapore. Email: elelc@nus.edu.sg

Funding information
National Key Research and Development Program of China, Grant/Award Numbers: R-2020-S-002, 2019YFB004800; RIE Advanced Manufacturing and Engineering (AME), Grant/Award Number: A18A4b0055; Advanced Research and Technology Innovation Center (ARTIC), Grant/Award Number: R-261-518-009-720

Abstract
With increasing requirements of the Internet of things (IoT) functioning with wireless sensor networks (WSN), a self-sustainable power supply has become an important pursuit in long-term working. The cantilever-based energy harvester is one of the most widely used devices for converting vibrations into electrical energy, while still challenged by restricted frequency bands toward practical applications. Here, a novel, feasible and cost-effective strategy for tuning the cantilever’s resonant frequency is proposed. By applying 3D printed thin sheets as extensions, the original single vibration mode is promoted into two relatively independent vibration modes tuned with extensions’ type, length, thickness, and proof masses. Hybridized piezoelectric-triboelectric nanogenerators are introduced to improve capacitor charging ability and potential vibration detection. Furthermore, a four-cantilever coupling design with different tuning parameters is investigated and enables wireless demonstrations of monitoring environmental temperature/humidity and carbon dioxide concentration, which is prospective as self-sustainable protection for workers in tunnels or underground constructions.

KEYWORDS
cantilever, frequency tuning, hybridized piezoelectric-triboelectric nanogenerator, internet of things, vibration energy harvesting

1 | INTRODUCTION

Along with the rapid development of energy harvesting technologies and their wide application in generating electric power from urban and natural environments, distributed potential and kinetic energies are promised to solve power supplies of numerous devices with Internet of things (IoT) designs and reduce carbon emissions.¹⁻⁵ These energy harvesters based on electromagnetic,⁶⁻¹¹ piezoelectric,¹²⁻¹⁷ and triboelectric,¹⁸⁻二十五 have been reported with rotation structures for winds or water flows,²⁶⁻²⁸ swing/fluttering structures for winds or
water waves, linear/nonlinear structures for vibrations induced from urban transportation or industrial machines. There into, as shown in Table S1, the vibrations are one of the most in-depth mechanical motions which reflect structural stability and mechanical failure, existing ubiquitously around daily life. Corresponding vibration sensing and energy harvesting device are commonly developed by optimized cantilever designs, ranging from micro-electromechanical systems (MEMS) fabricated beams to cost-effective piezoelectric patches. However, implementing frequency matching for high-energy conversion is still the key challenge in optimizing cantilever designs. Solutions for tuning the resonance frequency and widening the bandwidth have been reported by introducing nonlinearity and multistability, but those structures beyond the main body of cantilevers in prototypes have increased whole complexity and decreased practicability in harsh environments. In particular, the proposed prototypes of either setting stoppers to suppress amplification or installing magnetic pairs to achieve multi stabilities rely on extra elements within the operating space and need to sacrifice the cantilever’s degree of freedom. Besides tuning the cantilever’s resonance frequency with the tip mass, methods using attached stiffness like the pendulum structures and springs are also reported to meet various excitations, which also challenge the practical application of dynamic vibrations.

Furthermore, the cantilever designs also have been developed with triboelectric mechanism, which is a creative invention of cost-effectiveness in fabrication and high flexibility in multi-working modes. Corresponding triboelectric nanogenerator (TENG) has been reported to be applied in living and production like extracting vibration energy with a tapped cantilever, a triple-cantilever, and Newton’s cradle design. Moreover, the hybridized mechanisms attract more attention due to enhanced outputs and multiple-choice vibration sensing. For example, Wang et al. recently proposed a hybridized piezoelectric-triboelectric vibration module and achieved a self-sustainable vibration monitoring system for transportation. However, this module presented one single resonance frequency and only showed broadband characteristics when the TENG-based stopper worked at vibrations of higher acceleration, which may restrict the hybridized energy harvesting module from being applied in complicated scenarios like construction sites where exist various vibrations from different machines. Meanwhile, a reliable urban metro network system (UMNS) needs unceasing underground constructions and maintenance, where constructors are exposed to dust and gases that threaten their health. However, inadequate electric supplies in harsh environment are insufficient to sustain impeccable detections. Since the human body and natural environments possess various forms of vibrations, energy harvesters along with IoT nodes based on vibration energies can be potentially adopted to improve underground safety in smart cities.

In this work, a facile strategy of tuning cantilever resonant frequency has been developed with 3D printed cost-effective sheets and hybridized piezoelectric-triboelectric-electric mechanism is built on the cantilever without sacrificing the cantilever’s freedom. The simulations and test results have illustrated that advanced cantilevers obtain two resonance modes and resonant frequencies, which can be further adjusted by mass weight and show strong flexibility. By building the hybridized energy harvesting part on the cantilever’s area, the resonant frequency and corresponding amplification remain at the same level. Capacitors’ charging performances are improved with the hybridized mechanism. Through the electric power harvested with the hybridized energy harvester and stored in the capacitor, a Bluetooth module with a temperature/humidity sensor node is successfully powered for monitoring environmental changes on the mobile phone. A broadband coupling design is developed with four tuned cantilevers, achieving multiple responses to external dynamic vibrations. Demonstration of a carbon dioxide monitoring system for underground construction is achieved and displayed on the mobile phone, which is promised to be a portable alarm for protecting workers from CO₂ poisoning.

2 | METHODS

2.1 Fabrication of the cantilever-based hybridized piezoelectric-triboelectric nanogenerator

The sheets of different lengths and thicknesses are printed with PLA by 3D Printer (RAISE3D Pro 2). Corresponding lengths are set from 20 to 100 mm. And the thicknesses are set as 0.3, 0.5, 0.7, and 0.9 mm, resulting in actual thickness of about 0.45, 0.58, 0.76, and 0.93 mm. The width of the sheets is set as 20 mm to adapt to the base-cantilever. And Aluminum foil (0.05 mm thickness) is stuck to the sheets’ area that contacts the cantilever. Meanwhile, the base-cantilever is developed from a PZT biomorph (PANTPIEZO, 20 mm width, 60 mm length). Thin film PTFE (0.1 mm thickness) attached with Aluminum foil (0.05 mm thickness) is cut and stuck to both sides with crosswise PET adhesive tapes. Eventually, the sheets are fixed on the base-cantilever by the PET adhesive tape on the tips.
2.2 | Vibration and frequency tests

The vibration test platform consists of a vibration exciter (Brüel & Kjær, Type 4809), a power amplifier (Brüel & Kjær, Type 2718), and a vibration controller (Brüel & Kjær, Type 7541). Corresponding PC software is applied to set sweep frequency range and vibration amplitude, and the default acceleration is set as 1 g. The time-domain and frequency-domain outputs of piezoelectric generator are recorded by a 1X probe (GTL-101), while those of triboelectric nanogenerators are recorded by 1000X probes (TT-HVP-15HF). The output power and capacitor charging performances are measured by an electrometer (Keithley Model 6514) linked to a multichannel oscilloscope (Keysight, Model DSOX3034T).

3 | RESULTS AND DISCUSSION

As shown in Figure 1, the developed cantilever consists of a base-cantilever, two 3D printed sheets, and mass blocks attached to the tip of the base cantilever. In Figure 1A, three parts are summarized from the developed cantilever: the hybrid part for energy harvesting, the mass blocks for increasing the amplitude, and the tuning part equipped on a PZT bimorph's top and bottom side. As the developed cantilever is fixed in support and vibrated with the shaker, the sheets would interact with the base-cantilever and achieve contact-separation processes like teeterboard at the hybrid part’s area. According to Figure 1B, the top sheet will keep away from the base-cantilever as the tip vibrates downward, while the bottom sheet will remain away from the base-cantilever as the tip vibrates upward. The triboelectric nanogenerator can be built by introducing electrodes on the sheets and work as another energy harvester or potential vibration sensor. The working principles of the hybrid part are illustrated in Figure 1C, as following steps: (i) the sheets are close to the base-cantilever; (ii) as the base-cantilever vibrates down, the top sheet will remain away from the base-cantilever; (iii) as the base-cantilever vibrates up, the sheets do the opposite movements of the former step; (iv) as to the top-TENG, the positive charges flow from the dielectric electrode to the conductive electrode; as to the bottom-TENG, the positive charges flow from the conductive electrode to the dielectric electrode; the PZT biomorph generates inverse current in the circuit. The above steps and corresponding states repeat during the vibrations of the base-cantilever and respond to excitations operated on the fixed end of different frequencies.

To study the influences of 3D printed low-cost sheets (RAISE3D Pro 2, thickness setting: 0.3 mm) on the base-cantilever, the evolved designs are tested and illustrated in Figure 2. As a result, 10 mm out of 60 mm of the base-cantilever is used for fixing, and 10 mm from the tip is used for sheet attachment. For shortness, “E” notes for the extension and related length parameters are followed; “D” notes for doubling the extensions that increases the sheets’ effects; “C” notes for covering and corresponding sheets are ready for introducing TENGs. As shown in Figure 2A, the extension acts as the tip mass at the beginning and the resonant frequency migrates from 80 Hz of the base-cantilever to 68 Hz of the extension of 30 mm; the extensions longer than 40 mm have changed the single mode of vibrating about the base-cantilever and present two resonant frequencies, which both migrate to lower frequency as overall weight increases and drift more away from one another when the extension becomes longer. Figure 2B presents doubled extensions’ influences, and similar appearances are detected at doubled extensions of 40, 50, and 60 mm. Benefitting from the doubled extensions, the piezoelectric outputs are increased, and both resonant peaks reach the same level.

To develop contact separations for the TENGs, the covering extensions of different lengths are also studied in Figure 2C,D. From Figure 2C, the covering extensions of 50, 60, 70, and 80 mm, also act as the proof mass and occur similar decreased trends about resonant frequencies. And the resonant frequency of 73 Hz for 60 mm and 68 Hz for 70 mm are almost the same as 74 and 69 Hz for the extensions of 10 and 20 mm displayed in Figure 2A, which reveal that the covering part in the extensions has little influence on vibration modes. In contrast, two resonant frequencies are detected as the covering extensions of 80, 90, and 100 mm, which also occur at almost the same frequency positions as the extensions of 30, 40, and 50 mm in Figure 2A. By introducing the doubled covering extensions, two resonant peaks become comparable in Figure 2D. As a result, the developed cantilever obtains one resonant peak of 6.17 V at 24 Hz and another resonant peak of 6.1 V at 70 Hz. Compared with the base-cantilever resonant peak of 4.93 V at 80 Hz, the developed cantilever has gotten two responses and higher outputs. In addition, 3D printed thicker sheets
(H1: 0.5 mm; H2: 0.7 mm; H3: 0.9 mm) have been tested, resulting in similar vibrating modes but only in a longer length than the above results, and achieved vibration modes get a major difference in Figure S1. Thus, the sheets printed with set thickness of 0.3 mm and length of 100 mm are applied as double covering extensions to achieve modified vibration modes. The vibration modes also have been analyzed through Finite Elements Simulations (FEM) performed by COMSOL and shown in Figure S2, where results are consistent with the tests. In particular, two vibration modes are only found in longer covering extensions, which can be illustrated by the internal resonance that occurs due to nonlinear modal interactions between the base-cantilever and the covering extensions under external excitation.

Based on the above analysis, the proof mass has been applied to the developed cantilever with covering extensions, and the results are illustrated in Figure 3. The proof mass is prepared by demagnetization blocks (5 × 5 × 5 mm³, 0.77 g), and even numeral blocks (M1: two blocks; M2: four blocks; M3: six blocks; M4: eight blocks) are fixed on the tip in Figure 3A. As shown in Figure 3B, the proof mass has demonstrated a distinct influence on two vibration modes. For the extension-domain vibration mode at a lower frequency, the resonant peak presents light drifts and obvious enhancement; for the base-cantilever-domain vibration mode, the resonant peak migrates to a lower frequency and is enhanced as well. Related COMSOL simulation in Figure S3 leads to the same results, which reveal the approach of tuning working ranges of two vibration modes and enhancing outputs for energy harvesting. According to Videos S1 and S2, two vibration modes are displayed dynamically and confirmed with the internal resonance phenomenon between the base-cantilever and the covering extensions. Other cantilevers with thicker extensions in Figure S4 also show resonant peaks’ migration but fail to enhance simultaneously due to weak internal resonance in harder extensions.

Another important energy harvesting technology, triboelectric nanogenerators (TENGs), can add to the developed base-cantilever by attaching conductive electrodes to the covering extensions. And letters “P”, “T” and “B” in the following figures are used to represent the piezoelectric generator, top-TENG, and bottom-TENG in the hybridized piezoelectric-triboelectric nanogenerator. According to Figure 3C, due to a relatively considerable weight increase, the second resonant peak of the piezoelectric generator drifts to a lower frequency, whereas the cantilever with the proof mass has minimal effect. Corresponding TENGs also have been tested and displayed in Figure 3D, which obtain the same resonant frequencies as the piezoelectric part and result in higher outputs with the proof mass due to a larger vibration amplitude of the cantilever. The frequency-domain tests with 2 Hz/s are recorded by time and illustrated in Figure S5, where
obvious resonant frequency drifts and enhancements are recorded. Moreover, the frequency-domain tests based on the PZT bimorph and the covering extensions are illustrated in Figure S6, where two resonant peaks are observed but not at similar levels. So the hybridized device developed in Figure 3 obtains a balance between two vibration modes. Detailed outputs of the piezoelectric generator, top-TENG, and bottom-TENG have been illustrated in Figure 3E–G, respectively. The above three generators achieved maximum voltages of 14.67, 76.73, and 71.09 V at the initial resonant frequency of 23 Hz and achieved maximum voltages of 12.06, 67.03, and 60.58 V at the second resonant frequency of 37 Hz. By contrast, lower output voltages about the developed cantilever without the proof mass are obtained at the resonant frequency of 25 and 65 Hz shown in Figure S7.

Furthermore, three generators have been rectified with bridge rectifiers (DF10) and the results are illustrated in Figure 4. From Figure 4A–C, two resonant frequencies remain in the sweep frequency test of 2 Hz/s recording from start. And resonant peaks of 23 and 37 Hz are found in sweep frequency tests in Figure S8. From rectified outputs in Figure 4D,E, top-TENG, bottom-TENG, and the piezoelectric generator have delivered averaged outputs of 29.5, 39.7, and 15.5 V at 23 Hz, and 28.6, 42.3, and 12.7 V at 37 Hz. Corresponding currents are also tested and shown in Figure S9, and result in a higher value at 37 Hz than 23 Hz due to changed internal

---

**Figure 2** Studies of structure parameter for tuning resonant frequency (i: structure schematic diagram; ii & iii: sweep frequency tests): (A) Length of the extension (E, from 20 to 60 mm). (B) Double extension (DE, from 20 to 60 mm). (C) Length of covering extension (CE, from 50 to 100 mm). (D) Double covering extension (DCE, from 50 to 100 mm)
By integrating three rectified generators with parallel connection, final outputs tested with the 1X probe have maintained the fair level of the piezoelectric generator. In addition, multi-selected energy harvesting technologies supply the potential approach of sensing vibrations with TENGs while extracting electric power via the piezoelectric generator.

In Figure 5, output power varied with different load resistances has been tested under two resonant frequencies of 23 Hz (Figure 5A) and 37 Hz (Figure 5B). Ultimately, hybridized piezoelectric-triboelectric nanogenerator has delivered the maximum output power of 4.28 mW under a load resistance of 23 kΩ and at 23 Hz, and 3.78 mW under a load resistance of 15 kΩ and at 37 Hz. Above different matched resistances also confirm the reversal trend about voltages and currents shown in Figure 4 and Figure S7. Benefit from the hybridized mechanism, capacitors’ charging performances under vibrations of 23 and 37 Hz in Figure 5C,D have been improved and are better than corresponding charging performances of individual energy harvesting technology shown in Figure 5 and Figure S10. As a result, a capacitor of 1000 μF can be charged to 9.46 and 8.42 V within 50 s. Furthermore, a demonstration of wireless environmental monitoring building on a Bluetooth module equipped with a temperature/humidity sensor node, of which Figure 5E is the corresponding schematic diagram. As confirmed in Videos S3 and S4, the Bluetooth
FIGURE 4  (A–C) Rectified sweep-frequency outputs of piezoelectric/top-triboelectric/bottom-triboelectric cantilever. (D) Rectified outputs and integrated output under resonant frequency of 23 Hz. (E) Rectified outputs and integrated output under resonant frequency of 37 Hz.

FIGURE 5  (A) Output power of original cantilever and cantilever with tuning parts under resonant frequency of 23 Hz. (B) Output power of original cantilever and cantilever with tuning parts under resonant frequency of 37 Hz. (C) Capacitors' charging under resonant frequency of 23 Hz. (D) Capacitors' charging under resonant frequency of 37 Hz. (E) Schematic diagram of hybridized piezoelectric-triboelectric nanogenerators powering the Bluetooth module. (F) Voltage curve of the Bluetooth module that is powered to monitoring temperature and humidity wirelessly under different resonant frequency.
module is powered after the capacitor of 1000 μF is charged to 3.5 V and the temperature/humidity data is sent to a mobile phone continuously and wirelessly. Detailed data displayed in an App is shown in Figure S11. Compared with a single vibration mode of the base-cantilever, the developed cantilever with hybridized piezoelectric-triboelectric nanogenerators has supplied two considerable vibration modes for energy harvesting and building a more feasible and self-sustainable IoT system to monitor environmental signals.

By applying different covering extensions of 100, 90, 80, and 100 mm to respectively tune four base-cantilevers in Figure 6, a frequency-broadband coupling design is developed and shown in Figure 6A. As to base-cantilevers of No. 1 to No. 4, which are fixed in the same support, resonant frequencies of 79, 85, 81, and 84 Hz have been shown in Figure 6B, and a frequency-broadband coupling is obtained after parallel connection. Tuned base-cantilevers with different covering extensions have been illustrated in Figure S12, where the results have again verified extensions’ frequency-tuning. Furthermore, in Figure S13, tuned frequencies remain at the same positions but with higher amplitudes when the acceleration increases. As to the four tuned base-cantilevers shown in Figure 6C, the broadband coupling is obtained as well as the remaining multiple vibration modes. In particular, three relatively independent peaks of 24, 35, and 49 Hz, as well as a coupling area with the other three relatively dependent peaks of 70, 80, and 93 Hz. The coupling design with proof masses is shown in Figure 6D. Three considerable peaks of 22, 29, and 36 Hz, and a relatively lower peak of 47 Hz are obtained. Thus, the corresponding FWHM (full width at half maximum) of 19.7 Hz has presented a 31.2% increment on base-cantilevers. Next, hybridized piezoelectric-triboelectric nanogenerators are introduced to four tuned base-cantilevers, and three considerable piezoelectric peaks shown in Figure 6E, valued with 13.8, 15.3, and 12.1 V, have remained at 23, 29, and 37 Hz, respectively. From Figure S14, the top-TENGs and bottom-TENGs also present similar peaks at the same positions, which supply another option for vibration sensing while piezoelectric generators are applied in energy harvesting. Moreover, in Figure 6F, the hybridized piezoelectric-
triboelectric nanogenerators can respectively deliver 14.5, 15.4, and 12.3 V at 23, 29, and 37 Hz. Moreover, these three peaks will increase when the acceleration increases, and reach 24.2, 23.2, and 22.0 V in Figure 6G when the acceleration is set as 2 g. The sweep frequency of 2 Hz/s has been recorded from start, and Figure S15 about integrated top-TENGs, integrated bottom-TENGs, integrated piezoelectric generators, and coupling generators also present characteristic peaks mentioned above.

To promote the frequency-broadband coupling design in vibration energy harvesting, a power management circuit (LTC3588-1) is applied in Figure 6H to charge a capacitor of 2F at a representative frequency of 23 Hz. As a result, this capacitor has been charged to 0.62 V within 8 min, which increases 158% by charging performance without the power management circuit. Furthermore, a demonstration of a self-sustainable gas monitoring system for tunnels and underground is built in Figure 6l, where an Arduino board and a carbon dioxide detection sensor module are powered with the electric power extracted from vibrations. The capacitor charged to 5.4 V in Figure S16 and Figure 6J is linked to the Arduino board and successfully powers the system. In this case, the device has undergone more than 828 000 cycles. The outputs of that device are measured and compared before and after this long-term continuous test. Initially, a maximum voltage of 15.53 V shown in Figure S15D is obtained, and after the continuously testing, a maximum voltage of 15.34 V is obtained in Figure S17, revealing the device's excellent durability with only ~1.2% output degradation. In Video S5, the abnormal change in carbon dioxide concentration from 400 to 1259 ppm is detected and sent to a mobile phone. In terms of practical applications, this self-sustainable system possesses the potential to work with vibrations in tunnels and underground construction.

4 | CONCLUSION

In summary, a facile and effective strategy is reported to tune the base-cantilever's resonant frequency, by simply applying 3D printed thin sheets and proof masses on the cantilever. Corresponding parameters like extensions' length, extensions' thickness, and equipped proof mass are studied, and resonant frequencies and operation bandwidths are tuned with substitutable extensions efficiently. The resonant modes are improved by the internal resonance effect, with the results consistent with COMSOL simulation. These advanced cantilever designs with covering extensions are then adopted to introduce hybridized piezoelectric-triboelectric nanogenerators for energy harvesting and potential vibration sensing. At last, two resonant peaks with enhanced vibration amplitudes and bandwidth are found at 23 and 37 Hz; corresponding capacitors' charging performances are also improved with the hybridized mechanism. A demonstration of wireless environmental monitoring is achieved by applying the developed base-cantilever to powering a Bluetooth module equipped with a temperature/humidity sensor node. To support smart city expanding, a broadband coupling design is created with four tuned base-cantilevers covered by extensions of different lengths. As a result, the prototype responses to multiple frequencies from a wide frequency range and is able to extract different vibration energies from excavators, bulldozers, and tunnel boring machines. Thus, a self-sustainable CO₂ gas monitoring system is achieved and presents practical uses for solving hidden safety hazards in tunnels and underground constructions by IoT functions.

AUTHOR CONTRIBUTIONS

Long Liu: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing - original draft, writing - review & editing. Qiongfeng Shi: Investigation, validation, formal analysis, visualization, writing - review & editing. Xinge Guo: Investigation, validation, formal analysis, visualization, writing - review & editing. Zixuan Zhang: Investigation, software, visualization. Chengkuo Lee: Conceptualization, methodology, supervision, project administration, funding acquisition, writing - review & editing.

ACKNOWLEDGMENTS

This work was supported by the research grant of National Key Research and Development Program of China, China (Grant No. 2019YFB2004800, Project No. R-2020-S-002) at NUSRI, Suzhou, China; the research grant of RIE Advanced Manufacturing and Engineering (AME) programmatic grant A18A4b0055 “Nanosystems at the Edge” at NUS, Singapore; the Advanced Research and Technology Innovation Center (ARTIC), the National University of Singapore under Grant (project number: R-261-518-009-720).

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

ORCID

Chengkuo Lee https://orcid.org/0000-0002-8886-3649

REFERENCES


**SUPPORTING INFORMATION**

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Liu L, Shi Q, Guo X, Zhang Z, Lee C. A facile frequency tuning strategy to realize vibration-based hybridized piezoelectric-triboelectric nanogenerators. *EcoMat*. 2023;5(1):e12279. doi:10.1002/eom2.12279