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Acoustic Triboelectric Nanogenerator: Design, First Results, and Opportunities for Frugal Robotics

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Résumé

L'innovation frugale prend de plus en plus d'importance en réponse à la pénurie de ressources et aux préoccupations écologiques croissantes. Dans ce contexte, nous avons étudié comment concevoir et développer une technologie de récupération d'énergie adaptée aux applications robotiques. Nous avons prototypé et validé de manière préliminaire un nanogénérateur triboélectrique acoustique (A-TENG), capable de récupérer de l'énergie à partir des sons et des vibrations ambiants. Ses caractéristiques ont été comparées à un dispositif piézoélectrique, et des cas d'utilisation potentiels ont été explorés dans le domaine de la robotique.

Abstract

Frugal innovation is gaining increasing importance in response to resource scarcity and growing ecological concerns. In this context, we investigated how to design and develop an energy harvesting technology suitable for robotic applications. We prototyped and preliminarily validated an acoustic triboelectric nanogenerator (A-TENG), capable of harvesting energy from ambient sounds and vibrations. Its characteristics were compared with a piezoelectric device, and potential use cases were explored in the field of robotics.

Keywords: *Acoustic energy harvesting, Frugal innovation, Robotics, Triboelectric nanogenerator.*

1 Introduction

Ecological concerns and resource scarcity are driving the demand for sustainable technological solutions. In this context, we explore frugal design principles for robotics. Frugal innovation, as described by T. Weyrauch and C. Herstatt [1], focuses on the design of low-cost systems centered on core functionalities and optimized performance levels. This type of innovation is rapidly expanding as a research topic in robotics [2], due to its economic benefits by reducing production and environmental costs. One obvious example of frugal systems is the electric kettle [3] that can switch off without electronics: when the water boils, some vapor comes in contact with a bimetallic part, heats it, and consequently changes its shape, stopping the power supply. Another example is a passive solar tracker [4], which uses shape memory polymer to orient itself in the direction of the heat.

For our system, the objective was to develop a passive solution. We therefore investigated various energy harvesting methods. Among the options listed by A. Harb [5], we focused on harvesting energy from motion and vibrations, specifically from acoustic vibrations. The goal is to develop a system capable of recharging itself in noisy environments such as industrial settings, highways, crowds, concerts, etc.

Piezoelectric and triboelectric generators are well-known in the scientific literature [6, 7, 8], and such technologies can typically generate power ranging from $100 \mu\text{W}$ to 10 mW [6]. Piezoelectric materials convert mechanical stress into electrical charge, and vice versa. The use of such materials for energy harvesting is well-established, and many systems, including piezoelectric nanogenerators (PENGs), are based on this principle [9]. These generators can be realized by placing a piezoelectric material on a membrane attached to the end of a resonator, which amplifies incoming vibrations [6]. While these materials are monolithic and easy to integrate into systems, they are often expensive, complex to manufacture, and in some cases, involve ecotoxic substances such as PZT.

The triboelectric effect refers to the transfer of electric charge between two materials when they come into contact or slide against one another. This effect is exploited in triboelectric nanogenerators (TENGs) for energy harvesting [10]. Unlike piezoelectric materials, TENGs can be produced at a lower cost and often exhibit higher sensitivity to environmental perturbations. Furthermore, their fabrication can be simple and accessible [11]. This simplicity is largely due to the possibility of manufacturing TENGs via 3D printing using fused deposition modeling (FDM) [12, 13, 14, 15]. However, identifying suitable material pairs that are both compatible with the printing process and capable of generating sufficient energy remains a significant challenge. Using 3D printing, Yuan et al. [16] were able to develop an acoustic triboelectric generator (A-TENG) capable of producing up to 4.33 mW of electrical power under 100 dB acoustic excitation.

In this work-in-progress article, we compare our prototype of a triboelectric generator (see Fig. 1), inspired by the work of Yuan et al. [16], with a commercially available piezoelectric generator. Finally, we discuss potential improvements to the A-TENG design and examine possible use cases for such systems in the context of frugal robotics.



Figure 1: Prototype of the A-TENG

2 Fabrication and Design

To fabricate the acoustic triboelectric nanogenerator (A-TENG) in Fig. 1, we adopted most of the parameters described in [16], owing to the simplicity of their design and its compatibility with 3D printing. We used conductive PLA from *Protopasta* as one of the triboelectric layers, and an FEP film as the membrane and the second triboelectric layer. Since the FEP film is non-conductive, an additional electrode was required to collect the generated charges. For this, we employed conductive paint from *Bare Conductive*, chosen for its low cost, and applied it to the membrane using a screen printing (serigraphy) technique.

The different components of the A-TENG were assembled onto a quarter-wavelength acoustic resonator to amplify vibrations at a specific frequency. This resonant frequency (f_{resonant}) is related to the height of the resonator by the formula:

$$f_{\text{resonant}} = \frac{c}{4h}$$

where c is the speed of sound in air, and h is the height of the resonator. We chose $h = 100$ mm, which yields a resonant frequency of approximately $f_{\text{resonant}} \simeq 750$ Hz, representing a compromise between compactness and low-frequency response.

An exploded view of the A-TENG and its components is depicted in Fig. 2. This version of the A-TENG was used for all experiments described in the following section.

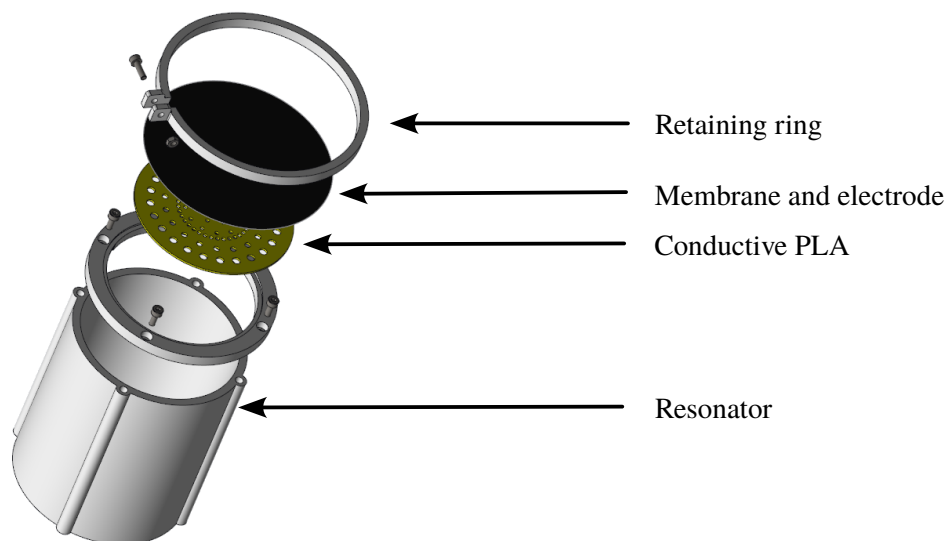


Figure 2: Exploded view and components of the A-TENG

Design Perspective A second version of the membrane was 3D printed using TPE (30 Shore 0), as shown in Fig. 3, to improve vibrational performance and enable full 3D-printability of the system. Advances in additive manufacturing now make it possible to directly print electrodes onto the membrane. However, attempts to apply the conductive paint to the TPE membrane were unsuccessful, as the paint did not adhere properly, resulting in discontinuities in the electrode and impaired electrical conductivity (Fig. 4).

In both prototypes, the conductive paint failed to bond effectively with the FEP membrane, leaving significant gaps in the electrode that could adversely affect electrical conductivity. Li et al. [17] reviewed

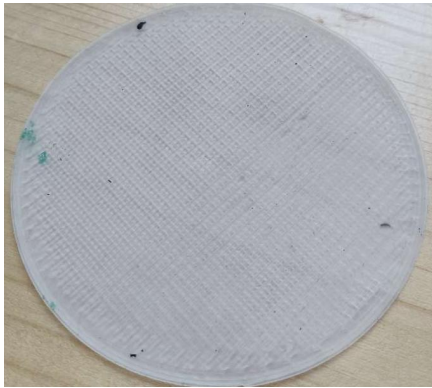


Figure 3: 3D-printed TPE membrane

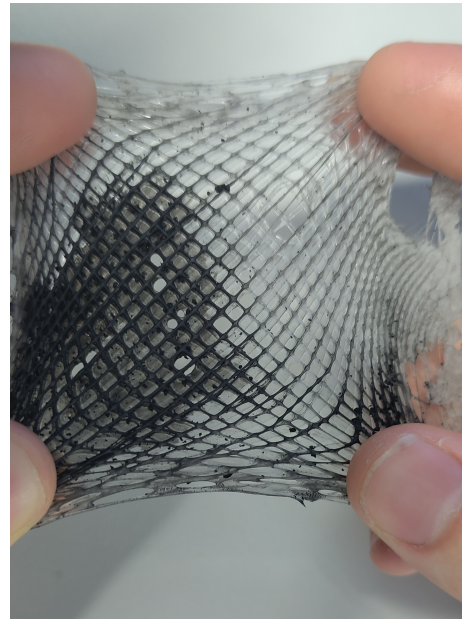


Figure 4: Stretched membrane test with conductive paint

recent advances in techniques and inks for triboelectric nanogenerators. Given our constraints in terms of cost, materials, and surface area, screen printing and spray coating emerge as the most suitable deposition methods. For inks, carbon-silicone rubber composites appear to offer optimal properties for screen printing applications.

3 Tests and Results

Electrical Performance The electrical performances of the triboelectric prototype were compared with those of a small piezoelectric slab with a resonant frequency of 75 Hz (i.e., MiniSense 100 Vibration Sensor, see its datasheet [18] for more information). In these first experiments, the piezoelectric slab was stimulated with a finger, making it oscillate and generate a sinusoidal voltage, while the triboelectric system was subjected to mechanical impacts on a surface, generating a non-sinusoidal and instantaneous voltage. While unloaded, both piezoelectric and triboelectric systems generated around 100 to 150 Volts peak to peak. In order to determine the output current, and thus the power output by these generators, a load was added in parallel with them. The generators were assessed under different load conditions to take into account their different intrinsic loads. For the piezoelectric system connected to a 100 k Ω resistor, the voltage signal went to a maximum of 5 V. This corresponds to a peak current of 50 μ A and a maximum instantaneous power of 250 μ W. Similarly, the triboelectric generator, tested with a 10 k Ω load, showed voltage peaks around 400 mV, yielding a peak current of 40 μ A and thus a maximum instantaneous power of 16 μ W. These values, while instantaneous, highlight that the piezoelectric generator currently offers superior performance. However, the triboelectric system remains competitive in cost and still holds potential for optimization.

Vibration, Sound, and Wind Excitation Beyond simple mechanical stimulation, three additional types of environmental perturbations were tested on the triboelectric system: vibration, sound, and wind. Under vibratory excitation (1–50 Hz) using a vertically vibrating platform, only a few hundred millivolts were generated, as vertical movement induces limited friction between active materials.

Sound-based experiments were more promising. Using various waveforms (sine, triangle, square, saw-tooth) across 1 Hz to 20 kHz, a significant voltage response was observed, especially around 537 Hz, with peak-to-peak voltages of 8.9 V (sine) and 8.5 V (triangle). These results were refined using a directional loudspeaker setup (see Fig. 5), allowing precise signal amplitude control.

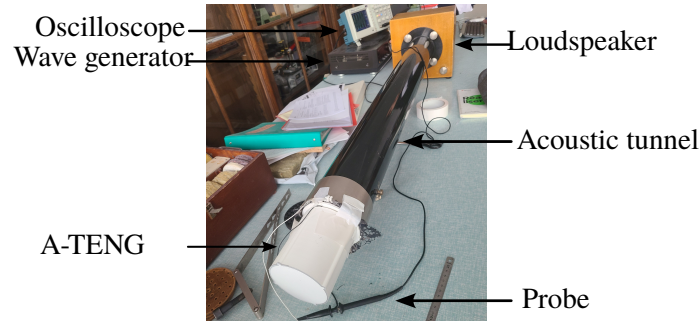


Figure 5: Triboelectric stimulation using a directional loudspeaker

Two resonance modes were identified at approximately 160 Hz and 630 Hz (see Fig. 6), with a maximum open-circuit voltage of 36.8 V_{pp} recorded. However, the instantaneous output power under load remained modest, around 340 nW.

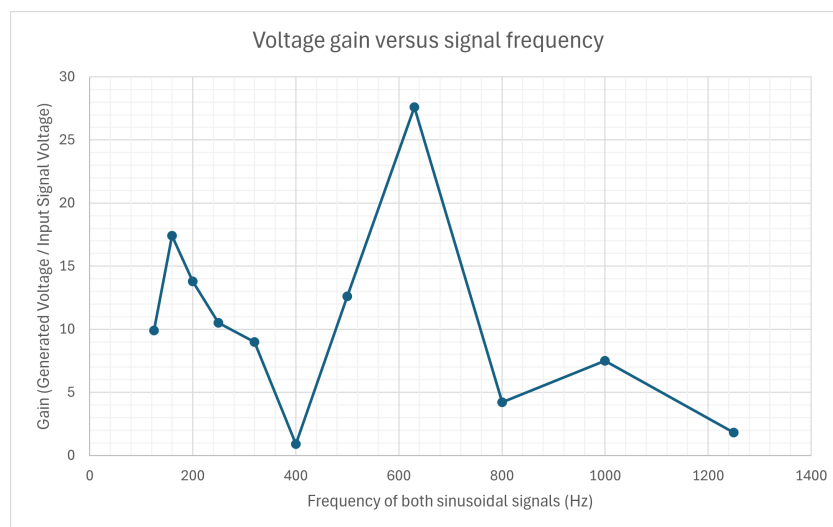


Figure 6: Voltage gain as a function of signal frequency

Experiments revealed that directing airflows onto the triboelectric membrane could generate up to 20 V_{pp}. More notably, using the downwash from a drone's propellers, voltages between 25 and 30 V_{pp} were recorded, demonstrating the potential to harvest otherwise wasted energy from drones, for indoor applications for example.

Despite all these stimulation methods yielding lower power compared to direct impact, they provided key insights into the system's resonance behavior and application potential.

Energy Storage Finally, energy storage was investigated using a diode bridge and a 22 μ F capacitor. Schottky diodes were preferred due to their low forward voltage drop, which is crucial for maximizing the harvested energy. The system was able to store up to 100 mV, albeit with notable limitations in

charge accumulation and retention. Though insufficient for powering energy harvesting ICs like the LTC3588 [19] in its current state, the triboelectric generator shows promise for future development in low-power energy recovery systems.

4 Improvement and Use Cases

Although the preliminary triboelectric generator developed in this study currently delivers low power – insufficient even to light a standard LED – several potential applications can still be envisioned.

First, the system shows promise as a vibration, wind, or sound sensor. As demonstrated in earlier tests, these physical phenomena induce measurable voltage outputs. By integrating the triboelectric element into a comparator-based circuit – possibly followed by a microcontroller or a simple LED – any perturbation can be detected and interpreted. Thresholds for detection could also be defined, enabling the system to act as a selective event-triggered sensor.

In scenarios with continuous environmental stimulation, such as concert halls or windy outdoor locations, the system could gradually charge a capacitor. The stored energy could then be released during consumption peaks, supporting low-power devices. This approach can be used for systems that do not need continuous energy consumption. One idea of such a system is autonomous beacons capable of signaling their position to mobile robots. This type of system works by generating ultrasound [20] or by using LED [21], which does not require much energy and does not need to be constantly emitting. For such use cases, energy harvesting efficiency must be balanced with mechanical constraints. For example, if mounted on a drone, the triboelectric device must harvest more energy than the additional energy expended by the drone to carry it.

With further optimization, the system could eventually supply ultra-low-power electronics, such as low-consumption microcontrollers or semi-active RFID tags. Enhancing the mechanical design, optimizing material properties, and improving energy storage and rectification stages would be crucial steps toward realizing such applications.

5 Conclusion

In conclusion, our triboelectric system remains in its early stages of development. Numerous aspects still require improvement, both in terms of design and practical implementation. Nevertheless, we have demonstrated the viability of the concept and identified several promising application areas where such a system could be effectively employed. We hope this work will serve as a foundation for future research and that triboelectric systems will find their place within the field of frugal robotics.

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