Animal hair based triboelectric generators and sensors

D. Blažević*[a], J. Ranta[a], A. Shaikh[b], Y. Mizukawa[a], J. Virkki[b], and P. Rasilo[a]
[a]Electrical Engineering Unit, Tampere University, Korkeakoulunkatu 3, Tampere, Finland;
[b]Augmentative Technology Group, Tampere University, Korkeakoulunkatu 3, Tampere, Finland

ABSTRACT

In the recent years triboelectric energy harvesting has gained a lot of research attention, and numerous triboelectric harvester designs have been proposed. We introduce a novel triboelectric energy harvesting architecture, where animal hair is used as the active material with a high positive charge affinity. To induce the triboelectric effect, animal hair is then brought into contact with polytetrafluoroethylene which in turn has a high negative charge affinity. In our approach, the electrodes are built as an array of individual charge collecting pins, which protrude into and interweave with the animal hair and skin and act as the net charge collector. The generators are built with two different approaches: a) by using 3D-printed structures with miniature electrode arrays and b) by using conductive fabrics arranged in a specific laminated structure. These are then tested in the laboratory in interaction with different animal hair materials with a novel methodology based on using a robotic manipulator test bed.

Keywords: Energy harvesting, Precision livestock farming, Triboelectric energy harvesting, Wearables, Wireless sensor networks

1. INTRODUCTION

Energy harvesting is the process of converting energy present in the environment like vibrations, water flow or solar radiation into a small amount of electrical energy. This energy is then used in-situ to power small electronic devices like wireless sensors which measure and transmit measured data to gateways or directly to the cloud in the scope of the larger Internet of Things concept. A large body of research has been dedicated to the study of different energy harvesting mechanisms which tap into different energy sources in the environment [1]. To exploit kinetic energy present in the source of vibrations or animal locomotion, researchers have proposed piezoelectric, electromagnetic, magnetostrictive and triboelectric energy harvesting concepts. Triboelectric energy harvesting has amassed significant attention from the research community in the recent decade due to simple and cost-effective generator construction [2]. In triboelectric energy harvesting, kinetic energy is converted into electrical energy in a combination of two effects – the triboelectrification effect and electrostatic induction. The triboelectrification effect facilitates the emergence of charge separation, or charging effect, on two triboelectric surfaces brought into frictional contact – one surface having a positive charge affinity and the other having a negative charge affinity. This friction-induced charge separation can then subsequently be converted into electricity via electrostatic induction when the two surfaces are brought out of contact or when they are partially separated. When the materials separate, electric potential is built up on electrodes covering the triboelectric pair surfaces. If a load is connected to these electrodes, an electric current will flow between the electrodes thus establishing a balance in the electric field. The harvester architecture can be established via four thus far identified operating modes [3]. Three modes incorporate paired electrode architecture: contact separation mode (CS), lateral sliding mode (LS), and the free-standing mode (FT). The fourth mode is a single electrode mode (SE) which requires external ground connection. In this paper, a new triboelectric harvester architecture is proposed, based on the paired electrode architecture, and inherent positive charge affinity of animal hair/skin. This harvester architecture is investigated with the intention of developing new kinetic energy harvesters for animal wearables like collars or leg straps [4] usually employed in the precision livestock farming agricultural concept [5]. Four different types of the harvesters are built based on this architecture and tested on a novel experimental test bed with three different animal hair types. These devices are then compared to devices exploiting two commonly used modes of triboelectric energy harvesting. The proposed concept is tested for energy generation capabilities.

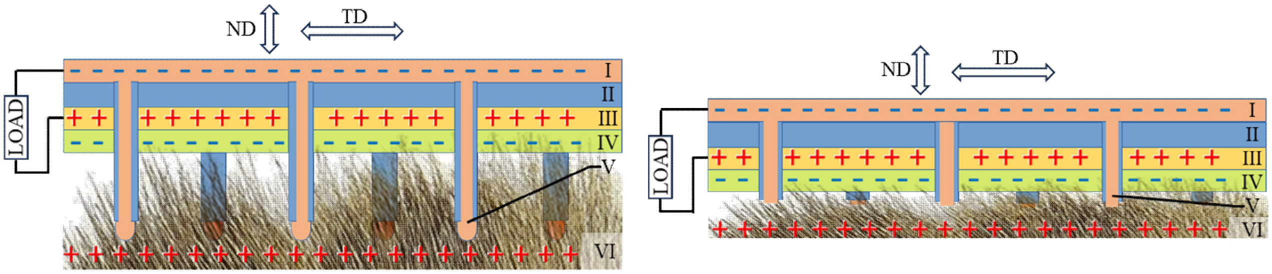
---

*david.blazevic@tuni.fi

Soft Mechatronics and Wearable Systems, edited by Ilkwon Oh, Sang-Woo Kim,
Maurizio Porfiri, Woon-Hong Yeo, Proc. of SPIE Vol. 12948, 129480B
© 2024 SPIE · 0277-786X · doi: 10.1117/12.3009810

2. THE INTERWEAVED ELECTRODE TRIBOELECTRIC HARVESTER CONCEPT

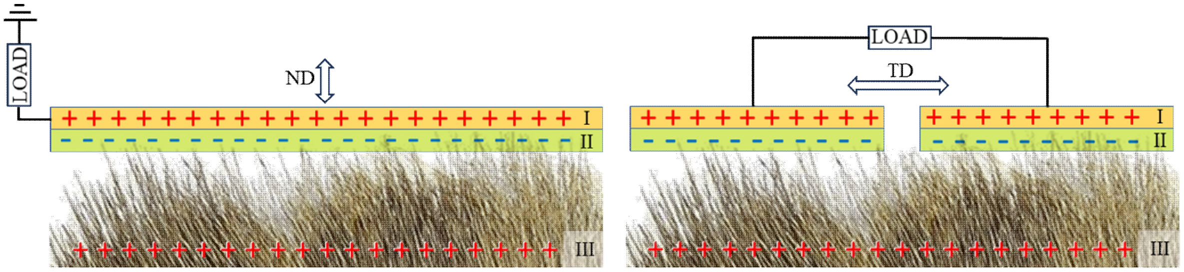
In our triboelectric energy harvesting concept, animal hair is used directly as one of the active triboelectric material layers. Animal hair has a positive charge affinity and places high on the positive spectrum of the triboelectric series [6]. If animal hair is brought into contact with compatible materials from the other side of the triboelectric series, namely polymers like polytetrafluoroethylene (PTFE) or fluorinated ethylene propylene (FEP), a triboelectrification effect occurs – an effect usually associated in our daily lives with destructive or unpleasant discharge effects. Commonly used modes of triboelectric energy harvesting with highest reported energy densities and figures of merit employ paired electrodes – one for each surface in contact [7]. Achieving a paired electrode configuration for CS or LS mode is straightforward if a fully packed, encapsulated, stand-alone triboelectric harvesting architecture is considered but becomes impossible if a living being's hair/skin is used as an active material. In these cases, it's impossible to attach a second electrode layer on the animal hair to form an electrode pair. Usually, this problem is solved by employing the SE mode [8].



a) b)

Figure 1. The interweaved electrode triboelectric harvester concept: a) Pin type for longer hair and b) Patch type for short hair/skin. Both types share identical parts: I) Top electrode for the positive charge affinity material (hair), II) insulator, III) bottom electrode for the negative charge affinity material, IV) negative charge affinity triboelectric material, V) pins or patches used to establish a potential difference between the top and bottom electrode and VI) Animal hair – material with a positive charge affinity. The arrows indicate excitation directions: ND – normal direction and TD – tangential direction.

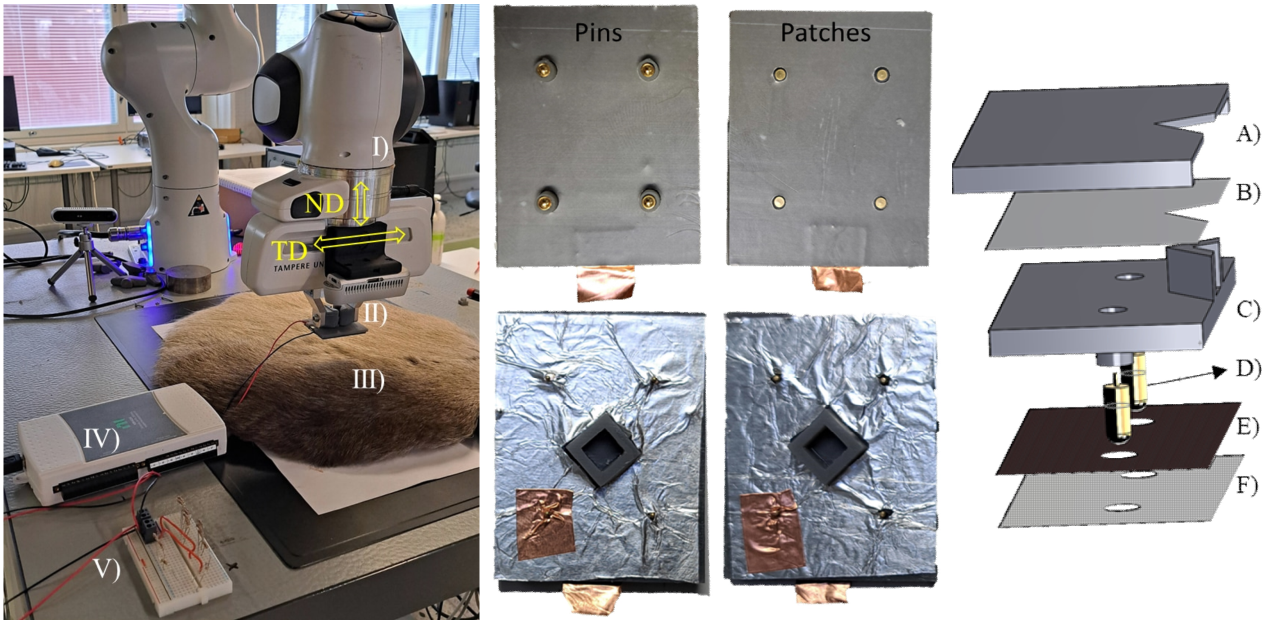
To solve this problem we have developed the concept of using multiple electrodes which interweave with animal hair in a matrix or comb like form and establish a potential difference on a displaced electrode layer which represents the hair electrode (Figure 1.). These interweaved electrodes, pins or patches of different sizes and heights are isolated from the negative charge affinity material and the accompanying electrode with a suitable material with a positive charge affinity. Additionally, electrodes could be made with a conductor with a positive charge affinity like aluminum. The matrix density could depend on the exact hair material density and could be sparse or dense, comb like or even hair like where the negative charge affinity material is made of thin hair-like strands which interdigitate with the animal hair thus increasing friction. It should be noted that exclusive CS or LS mode of operation are not expected in this case, but a combination of both modes will contribute to the triboelectric charging process.



a) b)

Figure 2. SE (a) and FT (b) triboelectric harvesting modes both having I) electrode/s for the negative charge affinity material, II) negative charge affinity triboelectric material and III) animal hair. The arrows indicate possible excitation directions: ND – normal direction and TD – tangential direction. Images adopted according to [3].

Hair material varies greatly in length and density across different animal species. Due to these variations the interweaved electrodes are made to be long, pin type, which protrude deep into the hair (Figure 1. a) or short, patch type, which protrude shallowly into the hair (Figure 1. b). Additionally, two different types of harvesters were built based on known FT and SE modes of operation [3] (Figure 2). Both harvesters are intended to operate without an electrode on the animal hair material and with the electric potential difference being established via an external ground (SE mode) or via a difference in potential on two identical but separated electrodes (FT mode). The potential difference occurs due to different charging on the triboelectric materials to which the electrodes are attached. In this paper we consider these devices to be excited by two possible directions of excitation, the normal direction which is perpendicular to the animal skin, and the tangential direction which is parallel to the animal skin. In the normal direction we additionally assume that the device is intermittently in and out of contact with animal hair while in the tangential direction of excitation the devices are in constant contact with animal hair.



a) b) c)

Figure 3. a) The robot manipulator test bed consisting of: I) Franka Emika Panda robot, II) 3-D printed grippers holding the triboelectric harvester, III) animal hair sample (reindeer hair in photo), IV) NI USB-6215 DAQ and V) a breadboard with a resistor load; b) the interweaved electrode triboelectric harvester photos showing bottom side (pins and patches) and top sides with aluminum electrode; c) half section view of an exploded 3-D model showing all layers and parts: A) cover cap, B) aluminum electrode, C) 3-D printed harvester base, D) gold plated pins – the interweaved electrodes, E) 3M 9711S double side conductive tape and F) PTFE triboelectric layer. The yellow arrows indicate the programmed excitation directions, ND – normal direction, and TD – tangential direction.

3. ROBOTIC ARM TEST BED AND PROTOTYPE BUILDS

This section describes the development of a robotic arm test bed used to provide kinetic excitation for the harvesters, and the detailed development of different harvester types. The harvesters are manually assembled and manufactured with 3-D printed parts and by using E-textiles.

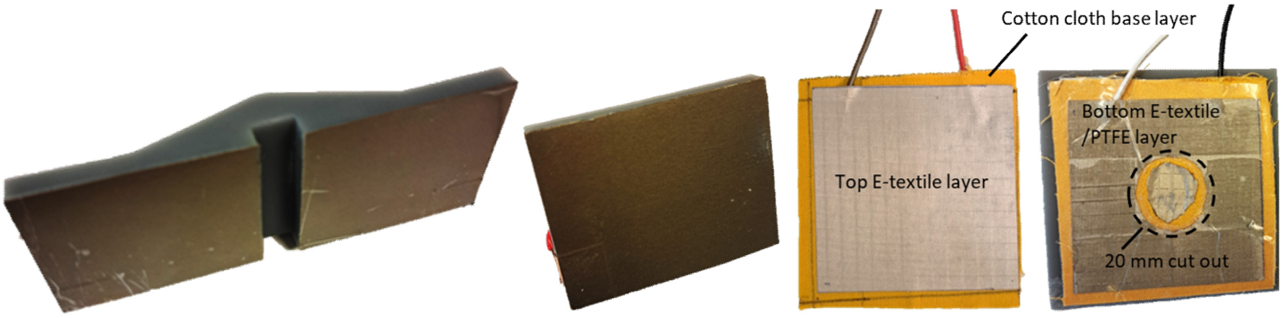
3.1 Robotic arm test bed

To establish a repeatable set of tests and produce excitation similar to animal locomotion a novel experimental test bed is conceived by employing the Franka Emika Panda collaborative robot manipulator (Figure 3. a). The robot end-effector, the tool at the end of robot arm, has a set of gripper fingers to which 3-D printed V shaped grippers were attached to hold the energy harvesters. The robot is programmed via the Franka Emika Desk web graphical programming interface to produce two types of excitations. The normal direction of excitation is programmed so that the end effector is brought from a position without contact into contact with animal hair sample on the table while maintaining a 5 N force threshold. The end-effector is then instructed to produce a ±20 mm vertical displacement contacting the hair at the low point and being out of contact with the hair at the high point of displacement. For the tangential excitation the end-effector is again brought into contact with animal hair and then instructed to move laterally with a ±20 mm horizontal displacement. The tangential excitation, which resembles the LS triboelectric harvesting mode, differs from the ideal LS mode presented in literature. For practical reasons, the harvester maintains constant contact with the animal hair emulating a possible collar-based triboelectric wearable for farm animals. The harvester leads are interfaced with the breadboard through a set of resistors which represent the load. The breadboard is then interfaced with the analog inputs of the National Instruments USB-6215 multifunction data acquisition (DAQ) device. In the case of the SE mode harvester the DAQ device's ground is used as the external ground to establish the potential difference. Three different types of animal hair were acquired as of the shelf products: reindeer, sheep, and cattle. Default Franka Emika Desk interface motion settings were used to drive the normal and tangential excitation which were later measured by an accelerometer to have acceleration amplitude of ± 0.15 g (gravitational acceleration, g = 9.81 m/s^2) at a frequency of 1.2 Hz for both excitation directions.

3.2 3-D printed triboelectric energy harvesters

The energy harvester base is 3-D printed with the Formlabs Form 3 printer and the Grey Pro prototyping resin (FLPRGR01). A prismatic holder is added on top of the base to facilitate gripping by the robot gripper. The triboelectric material used in the construction of the harvesters is 30 µm thick Saferlon® PTFE produced by Quanda plastic. The PTFE was smooth and not structured, in any way, micro or nano, to increase the friction with the animal hair. A PTFE surface area of 2000 mm^2 was chosen as a uniform surface value across all 3-D printed harvester base models. 9711S double-sided conductive tape manufactured by 3M was used to attach the PTFE layer to the 3D printed base and act as an electrode. First the PTFE was attached to the bottom side of the conductive tape and then the tape, with PTFE attached, was laser cut to exact dimensions with the Epilog Laser Fusion 75 W laser cutter. Once the cuts were done, the second adhesive layer of the conductive tape was used to attach the PTFE to the harvester base. Gold plated pins, Mill-Max Spring-Loaded Pin 7945 with a standard tail and Mill-Max Nail Head Pin 6381 were used as pins and patches respectively (Figure 3. b). The pins were press fitted into the holes of the 3-D printed base. These two initial prototypes employed four pins and four patches. On top of the base an aluminum electrode was glued with super glue and conductive silver glue was used to achieve electrical contact between the pins and the aluminum electrode. A small copper tape piece was inserted underneath each electrode prior to adhesion with the base to facilitate soldering of the lead wires. Once the sandwiching process was completed, a 3-D printed cap was glued on top of the harvester to isolate the top electrode. A half section view of the layer components of the interweaved electrode pin type triboelectric harvester is shown in Figure 3 c).

The FT and SE mode harvesters were designed by using the same materials as described in the previous paragraphs. As there is no electrode on the animal hair side in these harvesters, the pins and aluminum electrodes were not used in their construction. The PTFE layer and the double-sided tape were used in the same manner as described previously. The FT mode harvester had two layers of PTFE, 2 x 2000 mm^2, separated by a 10 mm gap and two lead wires for each electrode (Figure 4 a), while the SE mode harvester had a single layer of PTFE and a single lead wire (Figure 4 b).



a) b) c) d)

Figure 4. a) FT type harvester with a 10 mm gap, b) SE type harvester, c) top side of the conductive textile type harvester showing the electro-textile electrode, d) bottom side of the conductive textile type harvester showing the PTFE layer, electro-textile electrode and cloth base layer with a cut-out hole exposing the top electrode.

3.3 E-textile based triboelectric energy harvesters

The electronic textile (E-textile) based triboelectric harvester follows the same principles of construction as shown in Figures 1 a) and b). In this prototype, the top electrode acting also as a positive charge affinity triboelectric material is made of nickel-plated E-textile material Less EMF Shieldit Super Fabric (Cat. #A1220) as shown in Figure 4 c). This textile has an adhesive side that can be easily attached to the cotton cloth base material. The cotton cloth acts as an insulator between the top and bottom electrodes which are both made of the same type of E-textile material. Saferlon® PTFE produced by Quanda Plastic is used again as a negative charge affinity triboelectric material. To attach the PTFE to the bottom electrode and then the bottom electrode to the cotton cloth base, we employed the Holland shielding conductive (3205) double-sided adhesive transfer tape. A circular shape approximately 20 mm in diameter is cut out with the cutter's tip from the PTFE/electrode layer and the cloth base to expose the top electrode to the animal hair (Figure 4 d). The exposed top electrode has an adhesive layer which had to be covered with the same E-textile material so not to adhere to the animal hair. The top electrode has a surface area of 5 × 5 cm^2, while the bottom electrode is somewhat smaller – due to a ~20 mm hole diameter cut out. This prototype was built with two different thicknesses of the PTFE material, 30 µm and 100 µm. Both harvesters were attached on the top electrode side with a double-sided mounting tape to 3-D printed holders prepared to be gripped by the V-shaped grippers on the robot's end effector.

4. MEASUREMENT RESULTS

Harvester voltage measurements were performed for three different animal hair types (reindeer, sheep, and cattle), six different harvester prototypes and two different excitation directions, normal and tangential, programmed as described in Section 3. The chosen hair types are different in many ways and present a good range of possible hair varieties where triboelectric harvesting could be employed for energy generation or sensing in precision livestock farming applications. Reindeer hair having the thickest layer, then sheep and finally cattle hair with the approximate layer thickness (including skin) being: 20, 10 and 2 mm respectively. For all voltage measurements a resistor value of R = 100 MΩ was chosen based on the most frequent resistance values used in literature, because at this point impedance matching wasn't performed and resistor values weren't varied. Each experimental set-up consisting of a chosen animal hair type, harvester prototype and set excitation direction were repeated three times and lasted for 10 s each. For each of the three measurements average power was then calculated as $P = U^2 / R$ where U is the instantaneous voltage. The obtained values are compared in Figure 6 for the tangential direction of robot excitation and in Figure 6 for the normal direction of robot excitation. Table 1 summarizes the abbreviations used in the presented graphs and pairs them with prototype images presented in the text.

Table 1. Abbreviation legend

Abbreviation	**SE**	**FT**	**PA**	**PI**
Harvester type	Single electrode	Free standing	Interweaved electrode patch type	Interweaved electrode pin type
Prototype figure	Figure 4 a)	Figure 4 b)	Figure 3 b)	Figure 3 b)

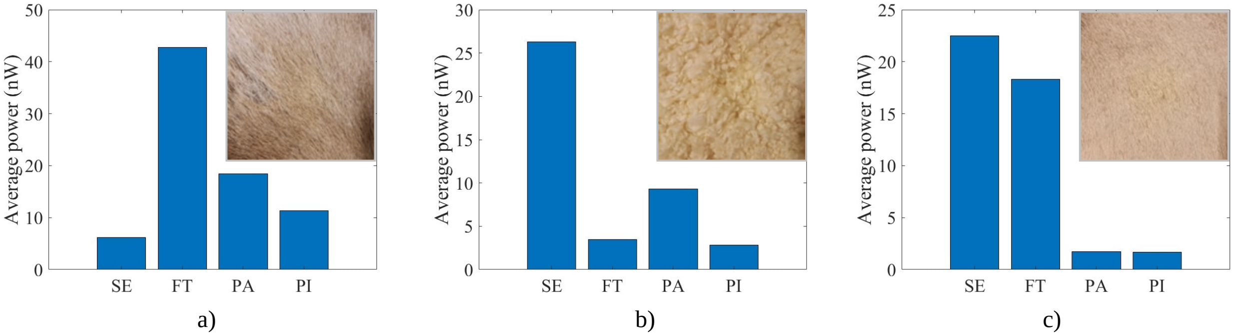
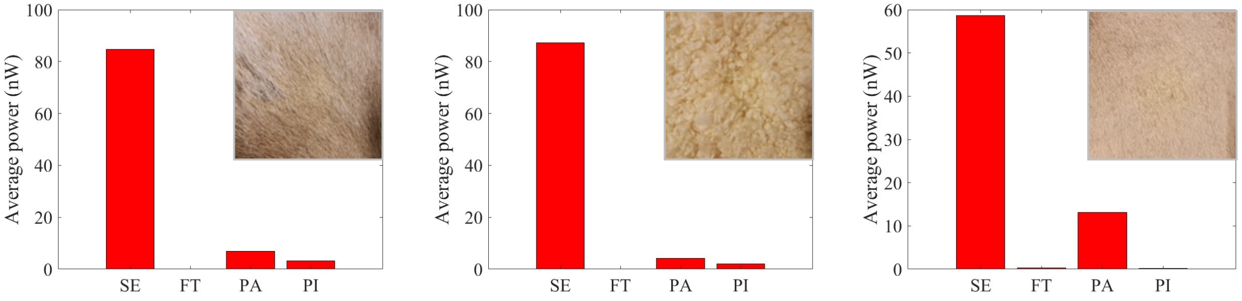


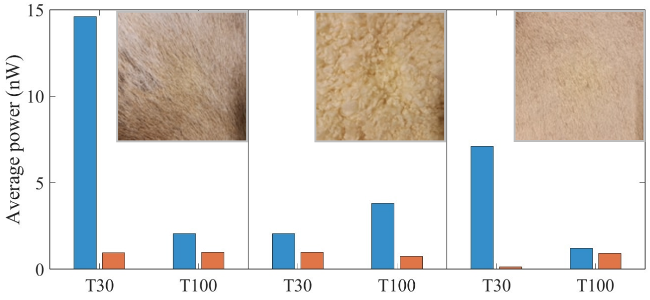
Figure 5. Averaged power results obtained from tangential excitation on three animal hair types: a) reindeer, b) sheep and c) cattle



a) b) c)

Figure 6. Averaged power results obtained from normal excitation on three animal hair types: a) reindeer, b) sheep and c) cattle

From the figures it can be observed that the SE harvester produces the largest amounts of power. We assume this is due to a stronger potential difference established by using the DAQ's ground terminal to complete the circuit for the SE mode. Surprisingly low power was produced on reindeer hair with the tangentially excited SE harvester. In the case of standalone harvesters which establish their own potential difference, the tangentially excited FT harvester produced better results when compared to PI and PA interweaved electrode harvesters. At this point its noteworthy to mention that this could be attributed to us wrongly interpreting the FT mode and designing the triboelectric surface area having 2 × 2000 mm^2. The FT harvester cannot be used while excited in the normal direction and therefore cannot be used in power generation in this way. This is due to the FT harvester depending on the charge density difference on both PTFE surfaces while they're in contact with the animal hair to establish the potential difference. In general, the shorter interweaved electrode PA type behaved in a better way producing more power that the PI type harvester which had longer electrodes. For both the PA and PI types of interweaved electrode triboelectric harvesters the normal direction of excitation is generally not favorable. This is due to the pin electrodes exiting the hair material upon separation, although the PA harvester, while being excited in the normal direction of excitation, worked surprisingly well on cattle hair (Figure 6 c). The PA and PI types have comparable results with the PA type outperforming the PI type in general and especially while excited tangentially in thicker hair (Figure 5 a and b). In the case of the PI type harvester under normal direction of excitation the electrodes do not penetrate the animal hair sufficiently and due to their height block the contact between the PTFE and the hair material thus indicating that the PI type is suitable for thick hair layers only.



a) b) c)

Figure 7. Averaged power results obtained with E-textile type harvesters under tangential excitation (blue bars) and normal excitation direction (red bars) with a PTFE layer thickness of 30 µm (T30) and 100 µm (T100) on three animal hair types: a) reindeer, b) sheep and c) cattle

Additional measurements were performed with the two E-textile type harvesters with a PTFE layer thickness of 30 µm (T30) and 100 µm (T100) and by following the same procedure as outlined in the previous sections. From Figure 7 it can be observed that for the E-textile type harvester the tangential direction of excitation is a more favorable and produces larger amounts of power than when excite in the normal direction. Dependency of the animal hair type on the triboelectrification charging effect efficiency can be observed from Figures 5., 6. and 7. Hair types with a uniform strand density and direction of growth like the reindeer hair and cattle hair will produce a larger triboelectrification charging effect than the non-uniform curly wool type of the sheep hair used in the experiments and under same conditions. This finding indicates that curly and non-uniform hair has to be addressed differently in the construction of animal hair-based harvesters. The results for normal and tangential directions of excitation are inherently different due to the way of establishing contact with animal hair and cannot be directly compared. Practical design consideration will have to be considered when designing animal wearables based on the interweaved electrode type harvesters as a combination of LS and CS modes is expected in practice.

5. CONCLUSION

This paper introduces a novel type of triboelectric energy harvester for precision livestock farming applications in which the key active triboelectric material with positive charge affinity is the animal hair. The novelty consists in having an arrangement of electrode pins or patches interweaving into the hair thus forming the hair layer electrode. The energy harvesters were 3-D printed and manually assembled into a multilayer structure. To test the performance of these harvester types, an experimental test bed was organized around a robotic manipulator which was used to provide kinetic excitation for the harvesters, and a new methodology was developed to validate the harvester performance. Additionally, E-textile harvesters were built and tested as well following the novel design principle. The measurements presented here are the first results obtained by employing this new methodology and offer initial insight into the workings of the interweaved electrode pin and patch type harvesters. Although the devices work, with the patch type harvester proving to be more successful of the developed varieties, a large number of unknowns is still left to be explored. The exact type, size and number of pins or patches is to be determined in future work. Different conductive tapes and electrode materials will have to be tested as well. The type of animal hair proved to influence the measured average power and the harvester construction should probably be adapted to the hair type (shorter hair – patches, longer hair – pins). The excitation levels used in the experiments were lower than the usual levels of acceleration found in animal locomotion. Due to this issue, in additional lab tests it was confirmed that larger accelerations significantly impact the voltage levels produced by the harvesters. The excitation acceleration levels, and the force applied on the animal hair is also to be varied and taken into account in future work together with a resistive decade box employed for varying different resistive load values. Finally, the surface layers will be structured to increase friction with the animal hair and the devices will be developed in a collar shape and tested on live animals.

ACKNOWLEDGEMENTS

This project received funding from the Business Finland - Research2Business funding framework (Project nr. 2140/31/2023). The authors would like to thank the Tampere University RoboLab for providing the robotic test bed.

REFERENCES

[1] Jawad, H. M., et al., “Energy-Efficient Wireless Sensor Networks for Precision Agriculture: A Review”, Sensors (17), 1781 (2017).

[2] Munirathinam, P., et al., “A comprehensive review on triboelectric nanogenerators based on Real-Time applications in energy harvesting and Self-Powered sensing”, Materials Science and Engineering: B (297), 116762 (2023).

[3] Wu, C., et al., “Triboelectric Nanogenerator: A Foundation of the Energy “, Advanced Energy Materials (9), 1802906 (2019).

[4] Blazevic, D., et al., “A farm animal kinetic energy harvesting device for IoT applications”, Proc. of SPIE Energy Harvesting and Storage: Materials, Devices, and Applications XII. (12090), 1209005 (2022).

[5] Tzanidakis, C. et al., “Precision Livestock Farming Applications (PLF) for Grazing Animals”, Agriculture (13), 288 (2023).

[6] Lacks, D. J. and Mohan Sankaran, R., “Contact electrification of insulating materials”, Journal of Physics D: Applied Physics (44), 453001 (2011).

[7] Zi, Y., et al., “Standards and figure-of-merits for quantifying the performance of triboelectric nanogenerators”, Nature Communications (6), 8376 (2015).

[8] Zhang, R., et al., “The triboelectricity of the human body”, Nano Energy (86), 106041 (2021).