Self-Powered Triboelectric Inertial Sensor Ball for IoT and Wearable Applications

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Abstract. Motion monitoring can provide useful information for rehabilitation or diagnostics purpose. Recently, triboelectric nanogenerator (TENG) has developed rapidly as a promising technology for energy harvesting and self-powered sensing. However, research effort of using TENG for multi-axis acceleration sensing is very limited. What is more, rotation sensing has not been achieved by TENG to date. Here we propose a 3-dimensional (3D) symmetric triboelectric nanogenerator based inertial sensor ball (TENG-Ball) for self-powered multi-axis acceleration and rotation sensing. The TENG-Ball has great potential in motion monitoring, internet-of-things (IoT) and wearable applications.

1. Introduction

Human motion information monitoring (i.e. biomechanical parameter monitoring) can provide useful physical and mental status information of our body, which can be further used for rehabilitation or diagnostics purpose [1,2]. Nowadays, the achievement of motion monitoring is normally by traditional inertial sensor module, such as accelerometer and gyroscope. However, the large power consumption of these sensor modules remains as one major concern towards green and sustainable developing future. In the past few years, enormous self-powered sensors based on triboelectric nanogenerator (TENG) have been extensively investigated for batter-less applications in internet-of-things (IoT), wearable electronics, healthcare and harsh environment monitoring. However, research effort of using TENG for multi-axis acceleration sensing is very limited. For instance, hybrid acceleration sensor (by triboelectric and electromagnetic) and spherical TENG based acceleration sensor was reported for only one-axis acceleration sensing [3-5]. To enable multi-axis sensing, a 3-dimensional (3D) acceleration sensor was proposed [6]. Yet the realization of multi-axis sensing is indeed from the three orthogonal integrated tube shaped TENGs, which greatly increases the device size and complexity. Furthermore, rotation sensing by TENG has not been reported up to now. Therefore, in this work, a 3D symmetric triboelectric nanogenerator based inertial sensor ball (TENG-Ball) is proposed for self-powered multi-axis acceleration and rotation sensing. The device also demonstrates the ability of hand motion recognition for virtual reality, game control and smart control interface. With the great sensing capability, the TENG-Ball can be used for a wide range of IoT and wearable applications.
2. Device design

2.1. Device configuration
The schematic diagram of a conventional gyroscope and the proposed TENG-Ball is shown in Figure 1a,b. The structure of the TENG-Ball is shown in Figure 1c,d. It consists of a spherical shell frame (65 mm diameter), four Al electrodes covering with polytetrafluoroethylene (PTFE) thin film and multiple steel balls with diameter of 6.3 mm. The multiple steel balls are adopted as movable mass and positive triboelectric layer. The fabrication of the TENG-Ball started from two hemi-spherical frames by 3D printing. Then Al and PTFE were attached on the inner surface and the device was sealed by polydimethylsiloxane (PDMS). The four electrodes are marked as Ex+, Ey+, Ex- and Ey-. Then Ex+ and Ex- are connected as Ex, while Ey+ and Ey- are connected as Ey. The photograph of the TENG-Ball before and after encapsulation is shown in Figure 1e,f.

![Figure 1. Schematic diagram of (a) a gyroscope and (b) the TENG-Ball. (c) Tilted view and (d) cross-sectional view of the device. Photograph (e) before and (f) after encapsulation.](image)

2.2. Working principle
The TENG-Ball is able to operate under various usage scenarios. The working principle of the device under in-plane vibration is shown in Figure 2a by side view. Only the inner electrodes and the PTFE thin film are shown in the schematic diagram. After contact, steel balls end up with positive charges and PTFE with negative charges due to different electron affiliation. When the steel balls are on the left electrode, electric potential difference arises and current flow appears. Then when the steel balls are on the right electrode, current flow is in the opposite direction. The working principle of the device under spinning or rotation motion is shown in Figure 2b by top view. Electric potential difference is sequentially induced on all the four electrons, resulting in current flow in the respective electrodes.

![Figure 2: Working principle of the device under (a) vibration and (b) spinning or rotation motion.](image)
3. Results and discussion

3.1. Acceleration sensing

The symmetric structure enables the TENG-Ball to function as a self-powered multi-axis acceleration sensor. Figure 3a-c shows the output from Ex and Ey for x, y and z acceleration sensing with 5, 15 and 25 steel balls encapsulated inside. For x-axis acceleration, voltage from Ex increases significantly at the beginning and gradually saturates. The result of 25 steel balls shows the best performance. The linear sensing range and sensitivity for x axis acceleration sensing is 4.87 g and 6.08 V/g. Meanwhile, voltage from Ey is negligible since no electric potential difference on Ey. Similar results are achieved for y axis with the linear sensing range and sensitivity of 5.06 g and 5.87 V/g. For z axis, voltage is generated from both Ex+ and Ey+ and the sensitivity is 3.62 V/g. The TENG-Ball shows multi-axis sensing capability that exhibits great potential for various complex motion monitoring.

![Figure 3: Output voltage versus acceleration in (b) x, (c) y, and (e) z direction.](image)

3.2. Rotation sensing

The TENG-Ball can also operate as a self-powered rotation sensor. As shown in Figure 4a, the TENG-Ball is fixed on a servo motor to generate rotation. Figure 4b shows the results of 5, 15 and 25 steel balls for rotation angle sensing from 10° to 180° at 280°/s. The output increases with the rotation angle due to higher electric potential difference. Figure 4c shows the results for rotation rate sensing at 180°. The inset depicts the waveform for rotation rate of 280°/s. The voltage also increases with the rotation rate. The device with 25 steel balls shows the rotation rate sensitivity of 3.5 mV/°/s.

![Figure 4: (a) Rotation sensing setup. Output voltage versus (b) rotation angle and (c) rotation rate.](image)

3.3. Hand motion recognition

Due to the capability of acceleration and rotation sensing, the TENG-Ball can be used for hand motion or gesture recognition. Figure 5a shows the photograph of the TENG-Ball held by a human hand for movement and rotation monitoring. Commercial accelerometer (ADXL325, Analog Devices) and gyroscope (ADXRS622, Analog Devices) are fixed on top to detect the actual acceleration and rotation. Output voltage is connected to oscilloscope for waveform recording when human hand is moving left, right, forward and backward or rotating clockwise and anticlockwise, as in Figure 5a. Figure 5b depicts the typical waveform for movement monitoring. For moving left, voltage from Ex first shows a positive peak and then several vibrating peaks while voltage from Ey is almost 0. On the other hand, voltage from Ex first shows a negative peak for moving right. This is mainly because...
when the TENG-Ball first moves to the left side, the steel balls are swung on Ex+ first, generating a positive peak in Ex at the beginning. For moving right, the steel balls are swung on Ex- first, generating a negative peak in Ex at the beginning. Similar results are observed for moving forward and backward. Figure 5c shows the results for rotation monitoring. For clockwise rotation, voltage from Ex first shows a negative peak and voltage from Ey first shows a positive peak. While for anticlockwise rotation, voltage from Ex first shows a negative peak and voltage from Ey also first shows a negative peak. This is due to the sequence of steel balls on the corresponding electrodes. In practice, the output pattern can serve as control signal for game control or smart control system.

Figure 5: (a) Photograph and (b) measurement results of moving forward, backward, left and right. (c) Photograph and (d) measurement results of rotating clockwise and anticlockwise.

4. Conclusion
In summary, a TENG-Ball is proposed for self-powered multi-axis acceleration and rotation sensing. The 3D symmetric structure is highly adaptable in various usage scenarios and can harvest energy from a wide range of ambient energy sources (vibration, rotation and human motions). The TENG-Ball shows multi-axis acceleration sensing capability with sensitivity of 6.08 V/g, 5.87 V/g and 3.62 V/g in x, y and z axis. Besides, the TENG-Ball can also serve as a self-powered rotation sensor with rotation rate sensitivity of 3.5 mV/°/s. Moreover, the TENG-Ball exhibits great performance in hand motion recognition. Looking forward, the proposed TENG-Ball can be a key component for the healthcare motion monitoring, smart control system, IoT and wearable applications.

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