A flexible slip sensor using triboelectric nanogenerator approach

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Abstract. With the rapid development of robotic technology, tactile sensors for robots have gained great attention from academic and industry researchers. Tactile sensors for slip detection are essential for human-like steady control in dexterous robot hand. In this paper, we propose and demonstrate a flexible slip sensor based on triboelectric nanogenerator with a seesaw structure. The sensor is composed of two porous PDMS layers separated by an inverted trapezoid structure with a height of 500 μm. In order to customize the sensitivity of the sensor, porous PDMS was fabricated by mixing PDMS with deionized water thoroughly and then removing water with heat. Laser-induced porous graphene and aluminium are served as the pair of contact materials. To detect slip from different directions, two sets of the electrode pair were used. Experimental results show a distinct difference between static state and the moment when a slip happens was detected. In addition, the output voltage of the sensors increased as the increase of slip velocity from 0.25 mm/s to 2.5 mm/s. The flexible slip sensor proposed here shows the potential applications in smart robotics and prosthesis.

1. Introduction
Human-like control of robotic systems draws great attention not only in industrial but also in people’s daily life. In order to realize human-like steady control in dexterous robot hand, slip detection is essential. A slip sensor is a device used to detect slide or pre-slide between robotic hands and held objects. Their performance directly determines whether robots can successfully complete a soft grasping task. Slip sensors with different principles have been developed to meet the requirements, including piezoresistivity [1], piezoelectricity [2], capacitance [3], photoelastic [4], thermal [5] and so on. However, most of them are based on rigid substrates. In recent years, triboelectric nanogenerators have been widely studied owing to their unique physical properties [6], such as self-power, simple structure and so on. In this paper, we propose and demonstrate a flexible slip sensor based on triboelectric nanogenerators. The sensor is composed of two porous PDMS layers separated by an inverted trapezoid structure. The sensor can not only realize slip detection but also static normal force detection by piezoresistive effect through laser-induced graphene electrode. The sensor we fabricated is flexible, sensitive and repeatable which may have promising applications in robotics.

2. Design and simulation
The fundamental working principle of triboelectric Nano-generators (TENGs) is a combination of triboelectric and electrostatic induction [7]. Contact electrification generates immobilized charges on polymer materials' surface which shown in Figure 1a, whereas electrostatic induction is the main mechanism that converts mechanical energy to electricity. In this work, we adopted the single electrode contact-separation mode of TENGs. First, the metal and polymer electrode contact together which generates charge transfer on the contact surface shown in Figure 1a. During the separation of two electrodes, residual charges on the polymer surface will generate an external electric field which will induce the charges in bottom metal. When a load resistance is connected between the metal and ground, there will be current going through it.

**Figure 1.** Schematic of the structure of the slip sensor: (a) Cross section view (b) 3D structure.

In our design, a seesaw structure of PDMS layer is adopted in the single unit in which each side of the seesaw serves as an isolated TENGs, as shown in Figure 1b. Two independent TENGs of single electrode mode in one unit was designed to detect the slip. The laser-induced graphene (LIG) is buried in the bottom PDMS layer which acts as the induction electrode. Laser-induced graphene is transferred from PI substrate into PDMS to keep its original porous structure [8]. The porous graphene structure has a large specific surface area which contributes to better induction charge capacity. In addition, the microcracking in porous laser-induced graphene results in the piezoresistive effect [9]. Therefore, the resistance of bottom electrode also has the potential to detect the static contact force.

The structure and static electricity simulation are conducted in COMSOL multiphysics. A spacer distance of 10μm is chosen. Zero contact pressure state of the structure is shown in Figure 2a. In order to clarify the phenomenon, we suppose that the sensor has been pre-charged to the original state. Figure 2b shows the static electric field on the bottom electrode when 8 nC/cm² [10] surface charge density is applied on PDMS. Average electric field potential of -42 volts and -40 volts is formed on each of the bottom electrodes. Then 100 mN contact pressure is applied on the left center of the unit. The contact force leads the deformation of PDMS structure, which generates a contact between the left electrodes. The static electric field becomes unbalanced due to the deformation, where the average electric field potential of left bottom increases to 25 volts and on the other side the average potential drops to -45 volts. The difference of the potential on the bottom electrodes will generate an output signal to indicate the specific contact of the electrodes. When a parallel movement happens on the sensors one side of the electrode will become contact while the other side will separate. Difference signal will generate from two electrodes.
Figure 2. Sensor simulation in COMSOL: (a) Initial state (b) 100 mN normal force applied on the sensor (c) Electric field of initial state (d) Electric field of sensor deformation.

3. Experimental

Figure 3. Fabrication process: (a) UV Curable structure by 3D printing. (b) Fill the mold with PDMS (c) PDMS after peel off (d) Deposit Aluminum (e) Clean Kapton PI substrate (f) Laser-induced graphene (g) Spin coating PDMS (h) Bonding two PDMS layer.
The fabrication process of the slip sensor is shown in Figure 3. A UV Curable Resin mold with pyramid structure is first fabricated by 3D printing. Then the mold is filled with a well stirred PDMS and deionized water mixture of 1:1 quality ratio (Figure 3b). After that, the mold is placed into a box at room temperature to stewing for 12 hours. Then the mold was put into an oven at 50 °C for 2 hours in order to evaporate the water inside the PDMS and leaves the holes. The SEM observation shows the average size of holes left in PDMS is about 12 μm, as shown in Figure 4. After evaporation, the PDMS is carefully demolded. A 200-nm-thick aluminum film is then deposited on the PDMS by magnetic sputtering method.

The bottom graphene electrodes of the sensor are generated by pulsed laser irradiation of polyimide (PI) films (Figure 3e)[8]. The LIG electrodes are directly writing on PI substrates through the laser. The sheet resistance of the fabricated LIG film is about 66.4 Ω/sq.

After the laser treatment, a thin film of PDMS is deposited on the electrodes surface by spin coating at 500 rpm. The PDMS was then cured at 80 °C for 2 hours. Then the PDMS layer is discreetly peeled off from the substrate together with LIG film. At last, the two layer of PDMS is bonded together with the assistant of oxygen plasma treatment.

![Figure 4. SEM image of the fabricated porous PDMS.](image)

4. Result and discussion

As shown in Figure 5, the sensor test platform consists of THORLABS Z825B displacement platform, MARK-10 Series 7 digital force gauges, and KEYSIGHT 34470A digital multi-meter. In order to test a single sensing unit, a small normal force of 180mN is applied to the center of the unit at the beginning. Then a 300μm parallel movement of the pressure head at the different speed is generated from the translation stage. KEYSIGHT 34470A is set at the load of 10MΩ and the test wires are connected between the bottom electrode and ground separately.

![Figure 5. Testing device and testing platform.](image)
Figure 6. Slip test results of (a) signal output of a single electrode (b) the repeatability of the device.

The result of single electrode output with slip speed of 2mm/s is shown in Figure 6a. Distinct signals were observed when a slip happened on the device surface. Good repeatability of the device is also obtained, as shown in Figure 6b.

Figure 7. Output voltage of TENG structure at different slip speed.

Figure 7 shows the output voltage of the slip sensor at different slip velocities varying from 0.25mm/s to 2.5mm/s. The peak output voltage of the sensor increased with the increase of the slip speed.

The static normal force response on LIG electrode was also tested by applying a normal force on one side of the unit. The test pressures begin with 3kPa to the end of 400kPa. The resistance of LIG changed linearly with pressure, as shown in Figure 8.

Figure 8. Relative resistance change ($\Delta R/R_0$) of the LIG structure at different pressure.

5. Conclusions

In this paper, we have demonstrated a flexible slip sensor based on single electrode mode triboelectric nano-generators. The sensor has a simple structure consisting of two layers of PDMS. Laser-induced graphene and aluminum are used as the electrode material pair. Experimental results show a distinct signal when a slip happens. In addition, the test of the piezo resistive effects of laser-induced graphene electrode indicates the slip sensor can be used to detect sliding and normal force simultaneously without changing the sensor structure. Further work will be conducted to minimize the size of the sensor to human fingerprints.
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