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Conformal direct-print of piezoresistive polymer/nanocomposites for compliant multi-layer tactile sensors

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Abstract

A conformal, compliant and multi-layer tactile sensor was built layer by layer using a hybrid manufacturing process including conformal Direct-Print (DP) technology and layer by layer soft molding process with a developed piezoresistive polymer/nanocomposite. A multi-layer conformal skin structure of the sensor was created using the soft molding process along with a highly flexible rubber material. Two layers of sensing elements were designed, where the sensing elements in the lower sensing layer were orthogonally placed against those in the upper sensing layer so that the sensing elements in two layers could cross each other with an insulating layer between them. A conformal printing algorithm was developed to advance the capability of DP technology. Thus, all the sensing elements were printed uniformly within the conformal skin structure. Several experiments on position detection were performed to evaluate the performance of the fabricated conformal sensor. The results showed that the sensor can detect locations of external forces applied on the sensor surface due to the multiple layers of sensing elements. It is concluded that the suggested manufacturing methods and developed materials are promising tools to develop conformal, compliant tactile sensors.

Keywords: Additive manufacturing; Conformal direct-print; Soft molding; Piezoresistive nanocomposite; Multi-layer tactile sensor

1. Introduction

Hybrid 3D printing with direct-print (DP) shows great manufacturing flexibility over traditional manufacturing processes to fabricate more complex and advanced structures [1]. Multi-layer tactile sensors have been considered as one of the applications of hybrid 3D printing [2]. These sensors deliver adequate tactile information from the interactions with the environment to a robot [3,4]. In parallel with the development of dexterous robotic hands, these tactile sensors play a critical role in improving the accuracy and control of robotic manipulators such as dexterous artificial limbs and prosthetic hands [5–8]. Despite numerous advances in the design and development of these sensors [3,4,9–22], issues such as robustness, complexity, flexibility, conformability, fabrication cost, as well as wiring topology, signal processing, packaging and assembly still limit their usage in general purpose applications [10,11,23].

Recent research with the advancement of a new flexible sensing material and fabrication processes has shown the possibility to overcome these challenges [9,20,21,24]. Printable and stretchable piezoresistive polymer/nanocomposites were developed through the introduction of nanoparticles into polymer matrices. In the authors' previous work [2,12], piezoresistive sensing nanocomposites were developed and successfully embedded within an elastomeric skin structure to produce large-area, distributed and stretchable multi-layer sensors using a developed DP process [12,20–22]. The DP process with the capabilities of printing low to highly viscous materials is considered as one promising process for printing 3D electronics. This process [25] has been used in many different applications ranging from biologically functional structures to 3D structural electronics, where fabrication procedures include the use of computer-controlled translation stages and pattern generator devices (e.g. a dispenser or jetting head) to selectively print 2D or 3D structures [26–39].

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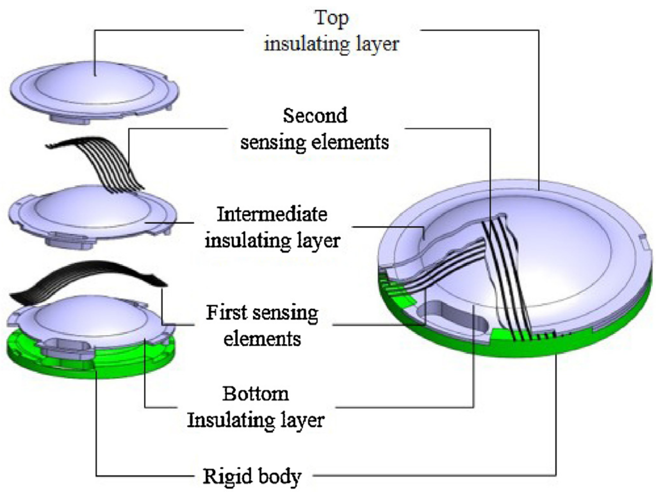

Fig. 1. Schematic of the proposed mechanically compliant, conformal, and multi-layer tactile sensor.

As the extension of the authors' previous investigations on the development of material and fabrication methods to create compliant and multi-layer tactile sensors [2,12,20,21,26], a conformal printing algorithm is presented to improve the capability of the DP process to uniformly print patterns on any freeform surface. Using the developed conformal DP process and a combined soft molding process, a multi-layer and conformal tactile sensor has been fabricated. The following describes the design of a conformal multi-layer tactile sensor, fabrication method, conformal printing algorithm, material synthesis, and characterization of the final fabricated sensors in more detail.

2. Sensor design

The suggested compliant tactile sensor consists of two layers of piezoresistive sensing elements arranged in an orthogonal configuration embedded into a fully elastomeric sensor body structure (Fig. 1). This sensor was designed with sections of a sphere, which represent conformal surfaces. Since both the structure and sensing layers are fabricated using the elastomeric materials, flexibility and conformability as well as the mechanical durability and compliance of the fabricated sensor significantly increase. Elastomeric materials also help prevent permanent deformation and preserve the natural mechanics when the sensor is deformed and released [40]. The working principle of the sensor has been presented in the authors' previous reports [9,12,20]. Briefly, a piezoresistive sensing material was developed by the dispersion of multi-walled carbon nanotubes (MWNTs) into a polymeric matrix. As a result of a uniform dispersion, conductive networks are formed inside the polymeric matrix. Consequently any deformation in the conductive matrix changes the number of nanotubes in contact; this changes the tunneling distance, which results in a change in the resistivity of the conductive network [41]. The sensing structure consists of 8×8 strips of sensing elements arranged in an orthogonal configuration. The number of sensing elements can be adjusted according to the number of taxels required for tactile sensing. The proposed configuration reduces the complexity of wiring topology and signal processing. For example, the sensor with 16 sensing elements (8 strips in each layer) needs only 16 signal outputs; however, it creates 64 taxels. Any of these taxels can be used to detect a two dimensional location of a force applied to the surface of the sensor.

3. Materials and experiments

3.1. Materials

TangoPlus FullCure® 930 (Objet Geometries Inc, MA, USA) as a commercially available photocurable resin was used for the backbone material of the sensing elements. This photopolymer is highly stretchable and tough with an elongation of 170–220% and a shore hardness of 26–28. To introduce piezoresistivity within this photopolymer, industrial-grade MWNTs (NanoLab, Waltham, MA) were dispersed into the photopolymer. SkinFlex III (BJB Enterprises, Tustin, CA) as a polyurethane casting rubber was used for the sensor body (Fig. 1). This casting rubber has properties desired in the compliant sensor such as stretchability with an elongation of 820–930% and a shore hardness of 5–25.

3.2. Preparation of a photocurable CNT/prepolymer solution

A prepolymer/nanocomposite was prepared with the dispersion of 0.5 wt% of MWNTs into a solution of 0.1 mM of zinc protoporphyrin IX (ZnPP, Sigma–Aldrich, Milwaukee, WI) in dimethylformamide (DMF, Sigma–Aldrich, Milwaukee, WI). To do so, a sonicator (Q700, QSonica, Newtown, CT) with a power of 700 W, frequency of 20 kHz, and amplitude of 50% for 1 min in pulse mode (20 s on, 10 s off) was utilized. Simultaneously, a glass beaker with the prepolymer/nanocomposite was placed on a magnetic stirrer so that any localization of ultrasound energy around the tip of the sonicator was prevented [12]. The solution of 0.1 mM of ZnPP in DMF was used for noncovalent functionalization of the MWNTs [42] which directly affects the dispersion and the stability of solution and consequently the sensitivity and the conductivity of the sensing material. The TangoPlus resin was then mixed with the prepared solution using the same sonication process for another 2 min. After that, all the organic solvent was completely removed using a hot plate magnetic stirrer (VWR 10×10 ALU Hotplate 120 V, VWR, IL) at 80 °C for 48 h. Then, the MWNT/prepolymer solution was filtered using a 150 μm filter (Sterlitech, Kent, WA) and degased for 24 h using a vacuum pump (ME 4 NT, Vacuubrand, Germany).

4. Multi-layer fabrication of conformal, and compliant tactile sensors

A hybrid 3D printing with soft molding, conformal DP and photocuring processes was utilized to fabricate the proposed multi-layer sensor. In this hybrid process, a sensor was fabricated layer by layer to embed the sensing elements into the elastic body structure (Figs. 1 and 2). The following sections describe

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