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Flexible carbon nanotube nanocomposite sensor for multiple physiological parameter monitoring

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ABSTRACT

The paper presents the design, development, and fabrication of a flexible and wearable sensor based on carbon nanotube nanocomposite for monitoring specific physiological parameters. Polydimethylsiloxane (PDMS) was used as the substrate with a thin layer of a nanocomposite comprising functionalized multi-walled carbon nanotubes (MWCNTs) and PDMS as electrodes. The sensor patch functionalized on strain-sensitive capacitive sensing from interdigitated electrodes which were patterned with a laser on the nanocomposite layer. The thickness of the electrode layer was optimized regarding strain and conductivity. The sensor patch was connected to a monitoring device from one end and attached to the body on the other for examining purposes. Experimental results show the capability of the sensor patch used to detect respiration and limb movements. This work is a stepping stone of the sensing system to be developed for multiple physiological parameters.

1. Introduction

The development of a novel flexible sensor patch for sensing multiple parameters is described in this paper. The sensor patch utilizes polydimethylsiloxane (PDMS) as the substrate and a nanocomposite of PDMS and carbon nanotubes (CNT) as electrodes. PDMS had been substantially used [1–3] for the development of flexible sensors due to its low cost, non-toxicitiy, inertness and hydrophobic nature. CNTs were preferred as the conducting material over other metallic nanowires because of their biocompatibility, high flexibility, resistance towards temperature change, low stiffness, and high tensile strength.

Multi-walled carbon nanotubes (MWCNTs) were used for the experiments functionalized with carboxylic groups (-COOH). The functionalized MWCNTs have a better dispersing capability inside a polymer compared to unfunctionalized or single-walled carbon nanotubes (SWCNT). This leads to a better interfacial bonding between the nanotubes and the polymer resulting in a higher conductivity. Interdigitated electrodes were patterned on the nanocomposite layer, allowing for a non-invasive and single-sided strain measurement. The patterns were produced using CO_2 laser ablation [4,5]. Compared to other fabrication techniques like 3-D printing [6], photolithography [7], inkjet printing [8], etc., it excels at the ease of sample preparation without the need for any templates or additional material. This method fabricates very thin and flexible materials and can cut smooth edges which are approxmiately parperdicular to the surface. By attaching the sensor to the skin, respiration and limb movements were tested on different people as shown in the experimental results section, to verify its functionality.

The concept of sensors to monitor people's health and lifestyle has been capitalized since the past two decades [9,10]. Different types of sensors have been used to monitor the activities and physiological parameters of the individuals to understand and generate a pattern for human behavior [11–13]. Sensors with flexible substrates are one sector where prominent research work [14–17] has been done in recent times. Light weight, low cost of fabrication, long lasting capability are some of the reasons for their increased usage over rigid substrates. The sensors developed for smart home usage are mainly dedicated for single parameter monitoring purposes like PIR sensors [18], pressure sensors, etc.

Multiparameter monitoring is of great interest due to the disadvantage caused by sensors for individual applications. For example, the cost is largely reduced in using a multi-functional sensor. The sensor patch development shown in this paper is much simpler and easier to fabricate compared to previously developed sensors, which had been fabricated for multiple functions containing a coil [19–21] operating on a magnetic principle.

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Table 1
Comparison of different force sensing resistors available in the market.

Sensor	Size (mm)	Force sensing capacity (lbs)	Price ($)	Application
RB-Phi-121	25*11	11.24	45.00	Pressure-sensitive touch user interface.
Flexiforce A101 Sensor	15.6 * 7.6	10	34.00	Bed monitoring systems, force sensitive video games.
SKU: SEN-09376	3.5	4.49	14.28	Tactile sensor for robotic appendages.
SEN-09375	2.375* 0.75*0.5	2.24	6.75	Bicycle handlebar glove, human symbiotic robot.

Significant research work has also been done on the detection of joint and limb movements. The majority of them involves fixed sensors [22] or the study of an artificial robot [23] to analyze the human behavior. Wearable sensors [24] and accelerometers [25] are other techniques used to monitor human movement. Shoe sensors [26] and braces [27] are some types of wearable sensors used for monitoring of physical activities involving limb movements. The existing concepts have distinct disadvantages. Some would be wearable sensing devices required to be worn by the person at times; others would involve complicated gadgets working on specific computational algorithms involving an expertise to operate them. Thus, there is a need for a simple, non-invasive, sensing device which upon its attachment to the monitored region would precisely detect the movements, even on a smaller scale. Research work to monitor the rate of respiration has been done previously using devices with and without flexible substrates. The photoplethysmographic technique [28,29] is widely used for the detection of respiratory rate. But this technique is complex and requires technicians at the time of monitoring. Piezo-resistive [30], fabric attached sensing [31,32] and optical sensors [33] are other ways used to monitor respiratory rate. Technical complexity, cost and specific positioning of the subject during monitoring are some of the demerits of these techniques. Monitoring of respiration and other physiological parameters has also been done using PVDF-based piezoelectric sensors [34,35]. But the disadvantages of using PDVF are the strong temperature depending performance along with high hysteresis exerted by the sensors. There are different force sensors available in the market. Table 1 classifies them based on price, size and some applications related to physiological parameter monitoring. Typically, either the price of the sensors is very high or the sensor size is large. In this paper, we show the change in capacitance of an interdigitated electrode on a flexible sensor patch by simply attaching it to the lower part of the diaphragm of an individual. The inhalation and exhalation rates were monitored based on the strain induced on the sensor patch. This could be used for applications like the abnormality in the rate of respiration caused due to hypoxemia and hyperemia which can be analyzed by monitoring the change in sensor capacitance between a healthy person and a patient.

2. Theory

The working principle of the sensor is based on the deformation of an interdigital electrode structure. The capacitance of any parallel plate capacitive device can be generally expressed by,

$$C = {(\in_o * \in_r * A)}/{d} \quad (1)$$

where,

C is the capacitance of the interdigital sensor,

$\in_o = 8.85$ is the $\times 10^{-12}\ F{\cdot}m^{-1}$ is the permittivity of vacuum,

$\in_r$ is the relative permittivity,

A is the effective area, and

d is the effective spacing between electrodes of different polarity.

A change of d or A causes a change of the capacitance. This can be exploited to monitor a physiological event through the change in capacitance based on the deformation-reformation of the sensor patch. The exertion of tensile stress on the patch via a physiological

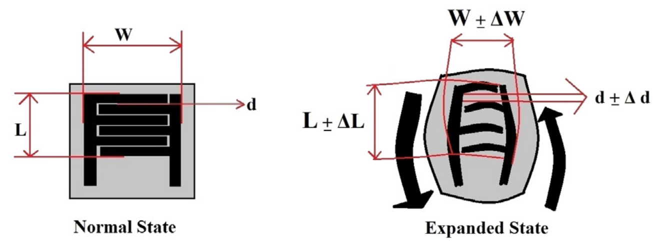

Fig. 1. Schematic design of the sensor patch made of a flexible PDMS substrate (gray) with electrodes made of a carbon nanotube/PDMS nanocomposite (black). Straining the sensor patch leads to a change of the sensor's length (L) and width (w) as well as the electrode distance d, resulting in a change of the measured capacitance value.

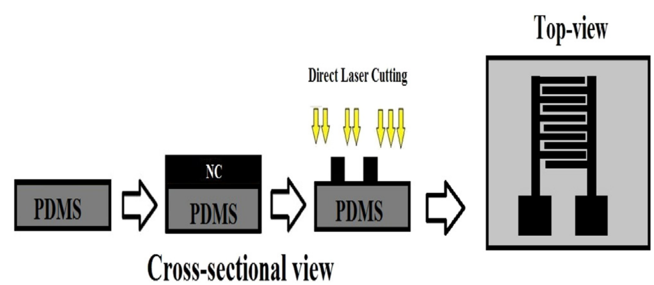

Fig. 2. Schematic diagram of the fabrication steps. PDMS: Polydimethylsiloxane. NC: Nanocomposite.

event changes the capacitance with respect to its normal position [36,37]. Fig. 1 depicts the notion. L and W stand for the length and width of the sensor patch, respectively. ΔL, ΔW, and Δd are the changes in length, width and interdigital distance of the sensor patch, respectively, caused when deformed. Using Eq. (1), the change in capacitance can be calculated as a function of change in length (ΔL), width (ΔW) and interdigital distance (Δd) as shown in Eq. (2).

$$\Delta C = f(\Delta L, \Delta W, \Delta d) \quad (2)$$

3. Fabrication and characterization of the sensor patch

The schematic diagram of the fabrication steps is given in Fig. 2. PDMS (SYLGARD ® 184, Silicon Elastomer Base) was cast at a ratio of 10:1 of base elastomer (pre-polymer) and curing agent (cross-linker) on a Poly (methyl methacrylate) (PMMA) template. The template was patterned using a laser cutter (Universal Laser Systems). PMMA was chosen because of its impassiveness towards PDMS and the cured material can be easily peeled off from the base without any additional steps. The thickness of the cast PDMS was adjusted to 1 mm by a casting knife (SHEEN, 1117/1000 mm). The sample was then desiccated for 2 h to remove any trapped air bubbles.

The sample was cured at 80^0 C for 8 h to form the substrate for the sensor patch. A mixture consisting of functionalized MWCNTs (Aldrich, 773840-100G) and PDMS was then cast onto the cured PDMS. 4% wt. of CNT was used after an optimization between the conductivity and dispersion of CNT into PDMS. Followed by the adjustment of the thickness of the nanocomposite layer by the cast-