Graphite-on-paper based bending sensor

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Abstract. Resistive bend sensors have been increasingly used in various areas for their interesting property to change their resistance when bent. They can be employed in various applications ranging from medical devices to structural monitoring. The graphite used is taken from pencil. This low cost graphite-on-paper based bend sensor has been developed to measure bending. The performance of graphite-on-paper sensor over varied graphite percentage and bending diameters was studied. The performance of the sensor for various graphite percentage was studied. It is found that the resistance increases as the resistance decreases and bending diameter increases.

1. Introduction
Flexible sensors are used in many applications such as structural monitoring and spine bending measurement. In structural monitoring, the raw data (i.e. voltage) measured from the sensor will be converted into structural response values such as displacement, strain and inclination [1]. Spine monitoring involves bending measurement is used for patients with problems associated with poor spinal conditions such as abnormal kyphosis (over curvature of the thoracic spine), lordosis (excessive inward curvature of the lumbar spine) or scoliosis (side to side curve of the thoracic spine) [2]. Flexible sensors can sense bending or deformation of material caused by applied forces. Strain or bend can be measured by various methods, namely; strain gauge [3], vibrating wire [1], fibre Bragg grating [1, 4] and Moire grids. Optical fiber-based sensors detect bending by measuring changes of intensity, phase, wavelength, or polarization of the light inside a bending optical fiber [4].

Resistive flex sensors are attractive due to its lightweight, sensitivity, low energy consumption and easy to operate [5]. The flex sensors have the ability to change its electrical resistance when there is a deflection. Silicon substrate can be made flexible by reducing the silicon substrate to submicron thickness through chemical-mechanical polishing process [6]. Due to the softness, lost cost and lightweight properties of paper materials, paper have received significant attention for the environmentally friendly substrate.

Graphite material can be used as a sensing material because it is made up of carbon and it is a good conductive material. Carbon molecule of the graphite material is capable of transferring voltage and current charge. Graphite material can be substitute as a sensor because the variation in resistance capable of reading and controlling the output desire. As a strain sensor, when there is a mechanical stress there will be deflection on the molecule structure of the graphite material. Mechanical stress or pressure will have variation in the level of deflection and different deflection will cause different resistance value. Inward deflection of graphite material will cause the molecules of the graphite material to be compressed which increases the conductivity between the molecules and decreases any resistance. Outward
deflection will cause the molecules of the graphite material to be expanded causing more resistance on the conducting structure. The resistivity generally decreases with increase of graphite content [7]. The electrical current flowing inside graphite layer is the tunneling current between the graphite grains, in which, the relationship between the resistance of graphite-on-paper and tunneling distance;

$$ R(l) \propto e^{\beta l} $$

(1)

whereby where $\beta$ is a function of the potential barrier height, and $l$ is the distance between the graphite grains. The tunneling distance is changed when strain is applied. Thus leading to the change of tunneling resistance [8];

$$ R(l + \Delta l) \propto e^{\beta (l+\Delta l)} $$

(2)

In this paper, a bending sensor is developed using pencil traces on paper. The pencil-on-paper approach offers a unique method to developing sensing platforms where devices can be easily fabricated and environmental friendly.

2. Experiment Setup
The schematic diagram of the sensor circuit is shown in Figure 1. In this circuit, ATMEGA328P microcontroller is used for controlling and interface. The sensor is shown in the circuit as a variable resistance. Another resistor, $R$ with the value of 45 kΩ is also added as the voltage divider. The voltage divider output is connected to pin A0 (ADC0/PCINT8) of the microcontroller. The Arduino circuit board is used to interface the microcontroller with the computer. This will give reading from the sensor using Arduino IDE through serial monitor process for continuous reading and serial plotter for a real time graph display. The sensor used pencil traces on paper. Two paper clips are attached at each end of the sensor to connect with the wires.

![Figure 1. Experimental setup. Insert: graphite based sensor.](image)

3. Result and Discussion
In this experiment, the sensor is bended inwardly. Figure 2 shows the variation of sensor resistance for different pencil grades. Pencil grades used in this experiment are 2B, 3B, 4B and 6B with graphite percentage of 74%, 76%, 79% and 84%, respectively. As shown in the figure, pencil with 74% of graphite exhibits the resistance ranging from 478 kΩ to 696 kΩ for 2.5 cm and 8.5 cm bending diameter, respectively. While pencil with 76% exhibits the resistance ranging from 244 kΩ to 334 kΩ for 2.5 cm and 8.5 cm bending diameter, respectively. For 79% and 84 % graphite percentage with the same
bending diameter, the change of resistance is 86 kΩ and 23 kΩ, respectively. The resistance range decreases as the graphite percentage increases. The sensor resistance increases as the bending diameter increases. However, the resistance decreases as the graphite percentage increases. Inward deflection of graphite material will cause the molecules of the graphite material to be compressed, thus increases the conductivity between the molecules. This in turn contribute to the decreasing of resistance. Figure 3 shows the resistance of the sensor in unbend condition.

Standard pencil leads are composed of graphite, wax and clay. The fine graphite particles are held together by clay binders. Wax is added for lubricant [9]. Pencils are classified on a scale from 9B to 9H. While pencil graphite material has many variations, each variation has different quantities of graphite, wax and clay. The hardness of the lead depends on the percentage amount of graphite and clay. For example, a soft pencil like 9B has higher quantity of graphite. While hard pencil like 9H has lower quantity graphite. The more graphite it contains the softer and the thicker it is. Figure 4 shows the EDS spectra of pencil leads correlating hardness with the fraction of carbon. Intensities of all of the spectra were normalized based on the carbon peak [10]. The figure shows the energy dispersive X-ray spectra (EDS) acquired on the cross-section for six different pencil leads. The intensities of the spectra were normalized based on the carbon peak to highlight the relative fractions of carbon to the clay. The clay which is used as binder mainly composed of O, Mg, Al and Si. The normalized spectra confirm that harder pencil leads contain a higher proportion of clay binders while softer leads contain a higher proportion of graphite particles. The higher carbon content in the softer leads results in darker traces on paper.

Figure 2. Resistance over varied bending diameter for different graphite percentage
Figure 3. Resistance for unbend condition

Figure 4. EDS spectra for different pencil grades [10].

Figure 5 shows the resistance read from microcontroller circuit. Whenever strain is applied on the sensor, there will be a change of resistance. As shown in the figure, there is strain applied due to the dip around 1960 µs.
Figure 5. Resistance plotted over time.

Figure 6 shows the bending resistance for different substrate. The substrates used are A4 paper and polyethylene plastic. The plastic shows higher sensitivity compared to that of paper. Thus, the sensitivity can be varied using different substrate.

Figure 6. Bending resistance for different substrate

4. Conclusion
We have demonstrated graphite-based sensor using pencil-on-paper approach. The resistance is measured over various bending diameter. The sensor able to sense the bending strain on the deformed material due to induced changes in resistance. The range of resistance can be controlled using different graphite percentage. The sensitivity can be controlled using different substrate. This sensor offers sensor which is sustainable, easily deployed and can be drawn into arbitrary patterns for numerous applications.
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