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CNT coated thread micro-electro-mechanical system for finger proprioception sensing

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Abstract. In this paper, we aim to fabricate cotton thread based sensor for proprioceptive application. Cotton threads are utilized as the structural component of flexible sensors. The thread is coated with multi-walled carbon nanotube (MWCNT) dispersion by using facile conventional dipping-drying method. The electrical characterization of the coated thread found that the resistance per meter of the coated thread decreased with increasing the number of dipping. The CNT coated thread sensor works based on piezoresistive theory in which the resistance of the coated thread changes when force is applied. This thread sensor is sewed on glove at the index finger between middle and proximal phalanx parts and the resistance change is measured upon grasping mechanism. The thread based microelectromechanical system (MEMS) enables the flexible sensor to easily fit perfectly on the finger joint and gives reliable response as proprioceptive sensing.

1. Introduction
Spinal cord injury, arthritis and stroke may cause patients to lose their proprioceptive sensing. Their nerve and muscle function will degrade hence reducing the sensing of motion control and position stimuli. Hand is an important part of human body that controls our daily activities. Stroke causes muscle weaknesses, loss of range of motion and impaired motor control [1]. Stroke patients usually have hand disorder; their muscles are weak, decrease range of motion and loss motor control [1]. In order to move as a normal person, they need to undergo rehabilitation therapy or be assisted by a device or machine. There are several equipments and methods that have been developed to help patients improve their capabilities [2-4].

Some devices have been developed to assist and monitor the motion of impaired body parts [5]. Most studies utilized robots to assist patients with hand disorder [4-6]. However, the utilization of robot may create inconvenience for the patient. A glove based therapy that integrates virtual reality program was developed for rehabilitation training [2]. The system is quite complex, using cyberglove that is embedded with 18 strain gauges and custom pneumatic actuator to provide force feedback to patient’s fingertips[2].

Carbon nanotube that was discovered by Iijima [7] has created tremendous effect in electronic, mechanical and sensor fields as carbon nanotube possesses remarkably high stiffness and strength [8]. It also has superior thermal and electrical properties [9]. Carbon nanotube has been implemented in
Micro-Electro-Mechanical system (MEMS) field as it can sense, control and actuate in micro level and can generate effect at the macro level [10]. This micro scale system which merges electronics and mechanical characteristics have usually been fabricated in silicon [11].

Fabric can show reliable results as a wearable sensor since it is flexible and can contact conformally onto human body. Therefore, in this paper, thread or yarn was proposed as an alternative sensing substrate material since it is inexpensive, flexible, lightweight, and can be easily sewn. This thread based sensor will be integrated into fabric by sewing technique.

2. Materials and Experimental Method
A yarn of 100% cotton thread was purchased from Asli Pari 100% Cotton Heavy Duty Thread (No.40, Combed Gassed Merchendized), Pakistan with 32 twist/inch (TPI). Multiwalled Carbon Nanotube (MWCNT) in the powder form with carbon content more than 70% and surface resistivity less than 900 Ohm.sq, as well as Sodium Dedocyl Sulphate, C_{12}H_{25}NaO_4S (SDS) surfactant and Sodium carbonate or soda ash, Na_2CO_3 were bought from Sigma Aldrich (USA).

Prior to coating MWCNT on cotton thread, the MWCNT was characterized using Transmission Electron Microscopy (TEM) to measure the number of layers of the MWCNT. The MWCNT powder was mixed with ethanol at weight ratio of 1:3 then, the mixture was ultrasonicated for 30 minutes at 100 rpm. 1 µl of the mixture was dropped on carbon grid (purchased from Ted Pella,inc) and dried at room temperature. Transmission Electron Microscope (TEM) imaging was then conducted on the MWCNT sample in Hitachi HT7700 TEM.

2.1. Pre-treatment of Cotton Thread
The threads function as substrate of the sensor. First, the threads underwent a scouring treatment to remove all the natural wax at the outer surface. This treatment improves the absorbency of the thread and removes impurities[12]. The scouring processes started by boiling 500 ml of distilled water. Then 10 g of soda ash was added to the boiled distilled water to produce soda ash solution at a concentration of 20mg.ml^{-1}. Then, 10 strands of 30 cm cotton threads were put into the mixture and stirred for 10 minutes. The threads were then rinsed with milipore water for several times until the pH of the rinsed water close to neutral level (pH 6.5-7.5).

2.2. Sensing Material Preparation
Prior to coating the cotton thread with MWCNT, dispersion of carbon nanotube was prepared by mixing 5 g MWCNT and 5g SDS to 50 ml of distilled water. The mixture was ultrasonicated for 30 min and was magnetically stirred for another 30 min.

2.3. Sensor Fabrication
The fabrication of thread sensor is illustrated in figure 1. The scoured threads were cut into 5 cm length and this thread was divided into gauge part (3 cm at the middle) and electrode part (1mm at each end). Then, the threads were dipped into 0.1 g/ml of carbon nanotube dispersion for 10 minutes. After that, they were dried at 60°C for 10 minutes. The dipping and drying processes were repeated 1-6 times based on number of coatings. The coated threads were then rolled with parafilm (elastic plastic) at the gauge part before continuing for another dipping repetition for electrode part. The electrode part of the sensor was dipped and dried for 10 times.
Figure 1. The fabrication process of the thread based MEMS. (i) Natural cotton thread initially coated with wax. (ii) After scouring, the wax at the surface is removed thus its absorbency was enhanced. (iii) The scoured thread was dipped in CNT dispersion and dried in oven. (iv) Cotton thread coated with carbon nanotube. (v) The middle part of the thread sensor was wrapped with parafilm to create electrode and gauge part. (vi) Dipping and drying process are repeated. (vii) Parafilm at the gauge part is removed. (viii) Thread sensor that consist of 3 cm gauge part and 1 cm electrode part at each end.

2.4. Sample characterization
Morphology of the carbon nanotube coated on the threads was characterized using Field Emission Scanning Electron Microscope (FE-SEM). The electrical resistivity of the sensor threads were measured using four point probe technique and were then converted into conductivity.

2.5. Sensor Calibration
The gold wire was attached to the CNT-coated thread using knot mechanism. Silver paste was placed onto the connection to improve the ohmic contact of the thread sensor and the wire. Then, the thread that was tied to the gold wire using silver paste was then placed into the oven at 60 °C for 1 hour to anneal the silver paste. To calibrate the thread sensor, the thread that was integrated with gold wire was positioned on the translational stage and clipped to the hold at both ends of the thread. The gold wire was then clipped by source meter probe to measure the change of resistance. Labview software was used to control the movement of the translational stage and reading of the sourcemeter (figure 2).

3. Results and Discussion
As seen in figure 3(a), the transmission electron microscope (TEM) image showed that the carbon nanotubes bundles are entangled to each other and individual tube of carbon nanotube has more than 10 layers of nanotube with an inner diameter of 5nm and an outer diameter of 15 nm. Carbon nanotubes in powder form are difficult to coat onto cotton thread, therefore, the powder carbon nanotube need to be mixed with aqueous solution to form carbon nanotube dispersion. As the van der Waal bonding between the carbon nanotubes are high, the carbon nanotubes tend to aggregate into bundles and it was difficult to produce good CNT dispersion [13]. Therefore, the surfactant (Sodium Dedocyl Sulfate) was used in this experiment to produce stable dispersion of solid in different medium [14]. The mixture underwent ultrasonicication first to provide a high local shear to fray the carbon nanotube bundles and then create a gap between the nanotubes [13]. Afterward, the surfactant molecules will fill the gap and make the carbon nanotubes separated.
The scoured cotton thread was then dipped into stable carbon nanotube dispersion. Figure 3 (b) present the Scanning Electron Microscope (SEM) images of carbon nanotube coating on cotton thread. From the image, it can be seen that the carbon nanotube was coated on the cotton thread’s surface. The high magnification of SEM image shows a high density coating of carbon nanotubes on the cotton thread’s surface.

Figure 3. (a) Transmission Electron Microscope (TEM) Image of the Multiwalled Carbon Nanotube and (b) Scanning Electron Microscope (SEM) image of the carbon nanotube coated on cotton thread.

Surface resistivity of the thread sensor was measured using four point probe method, and was then converted into conductivity values. The conductivity of the thread sensors of the gauge part coated with 1 time dipping to 4 times dipping is depicted in figure 4. The graph show that the conductivity of the coated thread is increased as the number of dipping at the gauge part is increased. The electrical conductivity of the thread sensor started to reach steady state value after 4 times of dipping. This related to percolation theory that after the volume ratio reach certain value, the electrical property of carbon nanotube change from nonconductive to conductive state [15].

Figure 4. The conductivity of the thread sensor with the gauge part coated with 1-6 dippings.

A graph of relative resistance change (measured using sourcemeter) versus strain is showed in figure 5, as a result of the procedure described in 2.5. As seen in figure 5, the thread sensor shown positive piezoresistive properties as increasing strain increases the resistance of the sensor. Gauge factor is used as indicator for determining the strain sensitivity of the sensor. Gauge factor is defined as the ratio of relative change in the resistance of the sensor (ΔR/R₀) to the applied mechanical strain, ε. A higher gauge factor means that the sensor is more sensitive to the changes in strain. The gauge factor of the sensor was obtained by measuring the slope of the graph. However, from the graph, the
sensor that was dipped for 2 times has the highest gauge factor than other sensors. This phenomenon might be because of the structure of cotton thread is porous and the carbon nanotube was not well distributed on the cotton thread.

![Figure 5](image5.jpg)

**Figure 5.** The graph of relative resistance change versus strain.

3.4. Sensor Testing
The sample of coated thread was sewn on the glove to test the application of sensor. The sensor thread was sewn on the glove with 10 cm electrode part (10 dippings) and 25 cm gauge part (5 dippings) on the index finger between middle phalanx and proximal phalanx. The electrode part of the sensor was connected to the probe of sourcemeter that was integrated to the Labview. The finger was bent slowly and the resistance change was recorded, as shown in figure 6. The resistance is increased as the finger is bent. Therefore, this sensor can be utilized to monitor the bending ability of the stroke patient during rehabilitation.

![Figure 6](image6.jpg)

**Figure 6:** The resistance change of the finger bending.

4. Conclusion
Hydrophobicity of carbon nanotube can be reduced by assist of surfactant. After immersed in carbon nanotube dispersion, absorbable cotton threads become conductive because the carbon nanotubes were attached on the cellulose fiber surface. This conductive CNT coated thread showed piezoresistive properties that changes its resistances when it bent. This condition can be applied for the proprioceptive sensor.

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