Building artificial muscle actuators from carbon nanotubes

An Na Yang Literature seminar November 07, 2013

The various types of natural muscle are incredible material systems that enable the production of large deformations by converting chemical energy into mechanical work. Inspired by such system, artificial muscle actuators that can reversibly simulate muscle-like motions such as contraction, expansion, and rotation, are of great interest.

Over this past decade, different materials[1] have been developed for the use as artificial muscles, e.g., shape memory alloys (SMA), electroactive polymers (EAP), piezoelectric ceramics. The performance of different types of artificial muscles exceeds that of natural muscle in many respects[2], making them particularly attractive for use anywhere where a muscle-like response is desirable. Commercial application of these materials is at an early stage, and only a few types are commercially exploited. The needs for new actuating materials are still present mainly as applications are restricted by the need for low weight, low maintenance voltage, fast response, long cycle-life, and high power density.

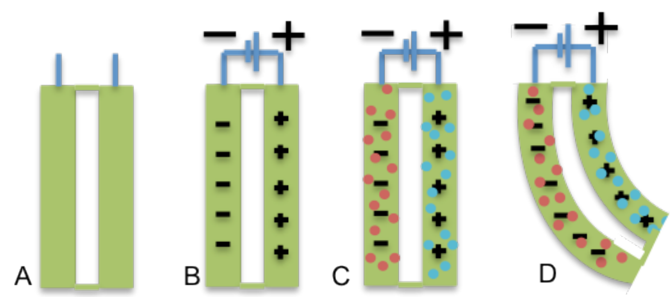

Figure 1. Double layer charge injection mechanism

Since the discovery of mulit-walled carbon nanotubes (MWNT) by Iijima and single walled carbon nanotubes (SWNT) two years later, a new material with remarkable properties was available for applications in various fields. Carbon nanotube's (CNT) exceptional physical and chemical properties include high conductivity, strong mechanical strength, large surface area, lightweight, and thermal stability.[3] For the first time in 1999, Baughman *et al*. demonstrated the use of sheets of SWNTs as an actuator using double-layer charge injection method.[4] Out of several actuation mechanisms for CNTs, double-layer charge injection is considered as the primary mechanism. In the double-layer charge injection actuation mechanism, the CNT acts as an electrode capacitor with charge injected into the CNT (Figure 1. B), which is then balanced by the electrical double-layer formed by movement of electrolytes to the CNT surface (Figure 1. C). The change of the charge on the carbon atoms results in changes of C-C bond length.[5] As a result, expansion and contraction of single CNT can be observed (Figure 1. D). Simultaneous use of CNTs for actuator and working electrode is advantageous in three ways: the actuator can have improved cycle life, response rate, and can operate at low voltage. However, occurrence of irreversible deformation under high load conditions is a major problem that needs to be improved in this system.

Subsequently, numerous studies devoted to building diverse CNTs based actuators were followed. In 2006, Ebron *et al*. presented fuel-powered artificial muscles.[6] A platinum catalyst coated cantilever based on a carbon nanotube electrode was used as a muscle, a fuel-cell electrode, and a supercapacitor electrode simultaneously. Hydrogen was used as a high-energy-density fuel source. The experiment demonstrated that a muscle converts chemical energy in a fuel to electrical energy and can use this electrical energy for actuation, store it, or potentially use it for other energy needs. The observed actuator stroke during chemically-driven charge injection was a 2 mm deflection of a 3 cm long nanotube cantilever in ~ 5 s as the nanotube electrode potential increased to ~0.8 V. About 0.035% length increase of NT sheet resulted from the potential change. This value is within a factor of 3 of the typical 0.1% maximum strain for commercial high modulus ferroelectrics, which usually require about 100V of externally applied potential for operation[7].

Recently, Foroughi *et al*. showed that an electrolyte-filled twist-spun MWNT yarn[8] (Figure 2), much thinner than a human hair, functions as a torsional artificial muscle in a simple three- electrode electrochemical system, providing a reversible 15,000° rotation and 590 rpm[9]. Immersing a twisted MWNT yarn and a counter-electrode in electrolytes and applying a voltage between these electrodes caused the yarn to partially untwist. Observed contraction of yarns was supposed to be largely driven by internal pressure associated with ion insertion. This system has shown great efficiency in torsional rotation with fast rate; However, it relies on use of electrolytes. As a result, the actuating system is restricted to a wet environment. Electrolytes limit operating temperature, voltage, and actuation rate. In addition, due to working electrolytes and required special packing, additional weight and volume reduce work density of the system.

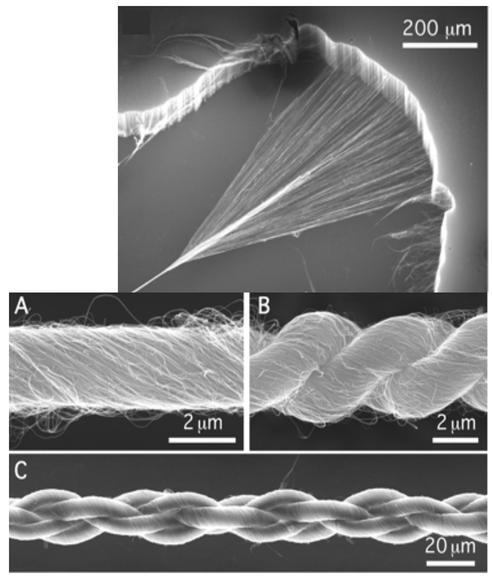

Figure 2. Twist-spun MWNT yarn. Torque stabilized (A) singles, (B) two-ply, and (C) four-ply.[8]

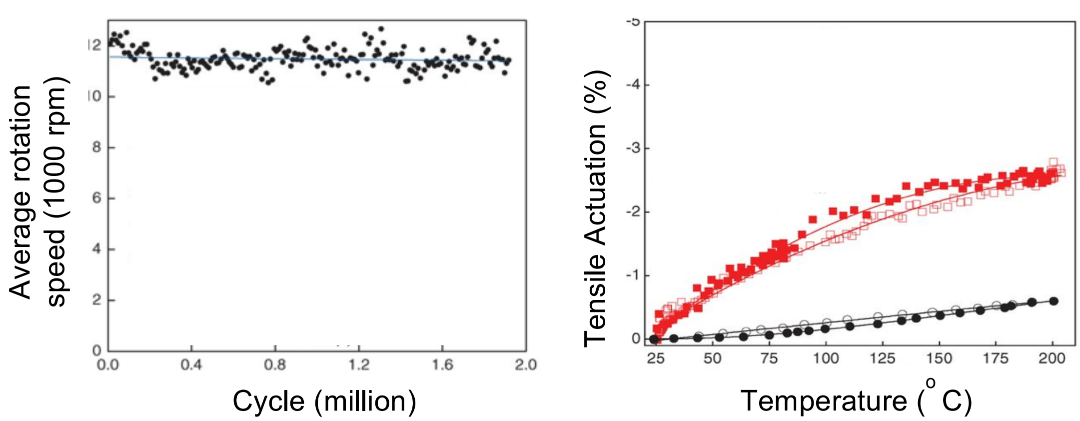

Figure 3. [Left] Average rotation rate versus cycle number. [Right] Tensile actuation strain versus temperature before (black) and after (red) guest wax infiltration.[10]

In 2012, Lima *et al* reported an electrolyte-free guest-filled twist spun MWNT yarn artificial muscle[10] that spun a rotor at an average of 11,5000 rpm, achieving 20 times higher than previously demonstrated by Foroughi *et al*. Also, the system delivered 3% tensile contraction at 1200 cycles/min and provided up to 27.9 kW/kg of mechanical power density during muscle contraction, which is 85 times higher than for natural skeletal muscle. More than a million cycles of tensile and torsional actuation have been performed without a significant loss of performance (Figure 3). Electrical, chemical, or photonic excitation of hybrid yarns changes guest paraffin wax dimensions and generates torsional rotation and contraction of the yarn host.

Compared with more common actuation materials, CNTs exhibit a series of advantages. Among others, actuation under low voltages, fast response rate, millions of cycle-life are especially significant benefits. Also, fuel cell powered CNT artificial muscle was demonstrated as well as CNT yarn based actuator with extremely efficient torsional actuation. Unique electronic properties, large surface area, high mechanical strength, and excellent chemical and thermal stability account for such advantages for CNT based actuators. CNT artificial muscles have potential application in intelligent robots, biomedical devices, and micro-electromechanical systems. [11]

Current research in CNT muscle field, which began about 15 years ago, is only at the basic and material research level. Progress towards the development of practical actuator technology in commercial markets can only be achieved when remaining challenges have been overcome. One of the most important challenges is the poor stress transfer between nanotube bundles and the outer and inner walls of MWNTs. This accounts for discrepancy in mechanical properties demonstrated for individual SWNTs and for the irreversible deformation occurring in double charge layer injection process. In all cases, this stress transfer can be improved by increasing the nanotube length, improving internanotube stress transfer.[12]

1. Madden, j. d. w.; Vandesteeg, N. A.; Anquetil, P. A.; Madden P. G. A. Artificial Muscle Technology. *IEEE Journal Of Oceanic Engineering* **2004,** 29, 706
2. I. Hunter *et al., Tech. Dig. IEEE Solid State Sensors Actuators Workshop,* **1992,** 178
3. Baughman, R. H.; Zakhidov, A. A.; de Heer, W. A. Carbon Nanotubes—the Route Toward Applications. *Science* **2002**, 297, 787
4. Baughman R. H.; Cui, C.; Zakhidov, A. A.; Iqbal, Z. *et al.,* Carbon Nanotube Actuators. *Science **1999**, 284, 1340*
5. L. Pietronero *et al.,* Bond-Length Change as a Tool to Determine Charge Transfer and in Graphite Intercalation Compounds. *Physc. Rev. Lett.,* **1981**, 47, 593
6. Ebron, V. H. *et al.,* Fuel-Powered Artificial Muscle. *Science* **2006,** 311, 1580
7. Lu, L.; Liu, J.; Hu, Y.; Zhang, Y.; Randriamahazaka, H.; Chen, W. Highly stable air working bimorph actuator based on a grapheme nanosheet/carbon nanotube hybrid electrode. *Adv. Mater.* **2012**, 24, 4317
8. Zhang, M.; Atkinson, K. R.; Baughman R. H. Multifunctional Carbon Nanotube Yarns by Downsizing an Ancient Technology. *Science* **2004**, 306, 1358
9. Foroughi, M. *et al.,* Torsional Carbon Nanotube Artificial Muscles. *Science **2011,*** 334, 494
10. Lima, M. D. *et al.,* Electrically, Chemically, and Photonically Powered Torsional and Tensile Actuation of Hybrid Carbon Nanotube Yarn Muscles. *Science* **2012,** 338, 928
11. Kosidlo, U.; Omastová, M.; Micusík, G.; Bauernhansl, T. Nanocarbon based ionic actuators—a review. *Smart Mater. Struct.* **2013**, 22, 1
12. Li, D. *et al.,* Molecular, Supramolecular, and Macromolecular Motors and Artificial Muscles. *MRS BULLETIN* **2009**, 34, 671