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Characteristics and Application of CMC Sensors in Robotic Medical and Autonomous Systems

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Abstract: Novel CMC tactile/proximity sensors made from carbon microcoils and elastic polymer, polysilicone YE-103.The sensor element can detect applied load by the change of electrical parameters with short response times of 0.3-0.5 s. The electrical resistivity increased logarithmically with increasing the applied load and decreased with increasing the hardness of matrix. The sensitivity of the SE-CMC sensor element was about 1mgf, while the sensibility of conventional capacitive sensors are 13-32pF/100 gf or 200-250V/100 gf accordingly, the SE-CMC sensor elements have three to four orders magnitude higher sensitivity than that of conventional capacitive sensors, The applications of the CMC sensors to medical, robotic, and autonomous system were developed. *Copyright © 2008 IFSA.*

Keywords: Tactile sensor; Carbon microcoil; Medical robotics; Minimal access surgery; Autonomous system

1. Introduction

1.1. MAS and Tactile Sensor Used

Eltaib and Hewit [1] defined MAS (minimal access surgery) to be an operative technique developed to reduce the traumatic effect of surgery; it is also known as minimally invasive surgery, keyhole surgery, endoscope surgery and laparoscopic surgery. In MAS the surgeon does not have his hands inside the operative field and the manipulations involved in the various procedures are carried out externally and transmitted to the operative site by long slender instruments inserted through small (5 or 10 mm diameter) access wounds. One of the openings is used to introduce a means of viewing the operative site and a light source to illuminate it. Images are displayed on a monitor. MAS offers many advantages over the more traditional open surgery. However, it possesses one very significant drawback—the loss, by the surgeon, of the "sense of feel" that is used routinely in open surgery to explore tissue and organs within the operative site. Applications of tactile sensing in MAS, both to mediate the manipulation of organs and to assess the condition of tissue, have been reviewed [1-4]. Some attempts to add tactile feedback to laparoscopic surgery simulation systems for MAS surgeon training are also described. The advantages of MAS surgery include—less tissue trauma; less postoperative pain; faster recovery; fewer postoperative complications; and reduced hospital stay. These advantages may be translated into a total health care cost reduction for commercial and governmental institutions. However, MAS has a number of disadvantages including—loss of tactile feedback; the need for increased technical expertise; a possibly longer duration of the surgery; and difficult removal of bulky organs.

Therefore, enhancing the tactile sensing capability of instruments used in MAS is a prime research area at present. The addition of tactile feedback to MAS simulation systems that are used to improve the practical skills of MAS surgeons is also an important requirement.

In MAS the working environment is a closed system containing soft tissue, living organs and body fluids as well as other instruments deployed by the surgeon. Since a tactile sensor for MAS is used inside the body, it must be reliable, biocompatible and waterproof and packaged in an appropriate useful manner. It must also be miniature and might need to be disposable. Thus, issues relating to cost and ease of assembly/disassembly must be addressed. Typically conventional tactile sensors used in MAS are Elastomer-based tactile sensors and silicon tactile sensors. However, there remain some inherent limitations. In this presentation, we reported a kind of novel tactile sensor made from carbon microcoils (CMCs), which has potential applications in MAS.

1.2 Carbon Microcoils (CMCs) and CMC Tactile Sensors

The carbon microcoils (CMCs), which was the first discovered by Motojima et al. at 1990, have an interesting 3D-helical/spiral structure such as a DNA or proteins [5-7], and are very interesting as novel functional materials for applying to electromagnetic wave absorbers, bio-activation catalysts, remote microwave-heating materials, high sensitive tactile sensors, etc. Human skin has many receptors, such as Meissnor' corpuscles, Ruffini corpuscles, Pacinian corpuscles, Merker's Discs, etc. under skin [8-12]. Meissnor's corpuscles, which is formed by a terminal nerve, have helical coiling patterns and dimensions similar to those of CMC, and present in two arrays under finger prints with the density of 1500/cm^2. If some stimuli, such as loads, pressures, stresses, etc. are applied to the human skin, the Meissnor's corpuscles are extended or contracted, the electrical properties are changed and the modified electrical signal depending on the stimuli can be formed. These signals are transported to brains via nerve and thus can be perceived the applied stimuli with a very high sensitivity and high discrimination ability. That is, the Meissnor's corpuscle is the most important receptor as the tactile sensing receptors of human hand. We found that the composite sheets of CMC with elastic polysilicone matrix showed high tactile sensing properties. For developing the high sensitive CMC tactile sensors, the electric and viscoelastic properties of matrix are important as well as the morphology, chirality and dimension of CMC [11-19].

2. Experimental of Sensor Preparation and Measurement

In this study, CMCs which have a coil diameter of 7-15 μm were synthesized by a conventional chemical vapor deposition (CVD) process using acetylene as a carbon source, the representative figure is shown in Fig 1. The detail preparation conditions are reported elsewhere [2-3].

CMC sensor elements (CMC/silicone rubber composite sheets) were prepared by mixing the different amount of CMCs (0-10 wt %, length of 0.3-0.5 mm) into silicone (Shin-Etsu KE-103), two Cu plates used as the electrodes were inserted into the composite sheets, and 0.5V AC from 40 Hz to 30 MHz. The electrical parameters were measured by an impedance analyzer (Agilent 4294A) when some loads were vertically applied on the whole CMC sensor elements. Usually, outputs at 100 KHz were plotted vs. the loads applied on the sensors.

3. Characteristics of the CMC Sensors

The representative SEM images of the CMC used as a sensor source and the extended view are shown in Fig. 1. To elucidate the influence of the extension on the electrical properties elastic CMCs, we used an impedance analyzer and measured the changes in the L, C, and R parameters as a function of the extension and contraction of the bulk SE-CMC sheets, and these results are shown in Fig. 2, in which the SE-CMC sheets were extended by 5 mm under the applied load and then contracted to the original coil length by releasing the load. Because the specimen was as-grown bulk CMCs in blanket-shape, individual CMCs did not extend at the same time at beginning of extension, thus, the measurement of electrical parameter changes was carried out since $\Delta L=1$, and ended also before fully contraction, also at $\Delta L=1$. It can be seen that the LCR parameters all increased with their extension and decreased with their contraction. The increase and decrease rates are almost the same and the change in the L and C parameters are very similar. Accordingly, it is considered that the changes in these electrical parameters of the bulk SE-CMC sheets during their extension or contraction is considered essential for obtaining the SE-CMC tactile sensing ability. It is noticed that the LCR parameters do not return to their original values after unloading. The coils had contacted with each other in an initial stage (before loading), were even entangled, but after applying the load, most coils were separated, some were broken, not due to the mechanical weakness but due to geometric position of the respective coils against the extension direction. As a result, some permanent change took place.

Fig. 1. Representative SEM image of double-helix carbon microocils (DH-CMCs).

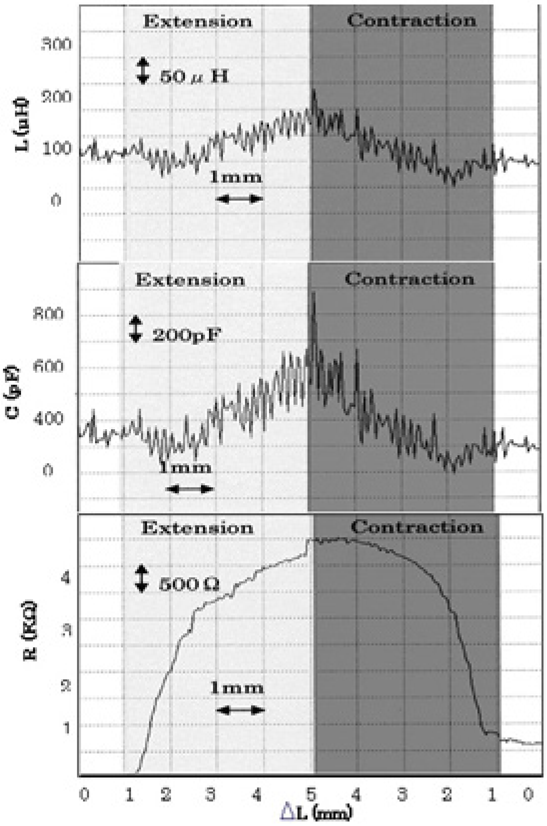

Fig. 2. Changes in LCR parameters of the bulk SE-CMC.
ΔL indicates the extended or contracted length of the SE-CMC from the original length (ΔL=0),
the gray zone is the contraction process [15].

By filling the CMCs into the elastic matrix, CMC sensor elements were manufactured as the following procedure: commercial elastic resin; polysilicone (Shin-Etsu, KE-103) and elastic epoxy resins (Dainippon-Chemicals, EXA-4850) were used as the matrix. The CMC used as a source of sensor element, which was prepared by the catalytic pyrolysis of acetylene, had double-helix structure with a coil diameter of 7-12 μm and a coil length of 300-500 μm. The CMC were uniformly dispersed in the matrix using a centrifugal mixer, de-bubbled in vacuum, molded and solidified to form thin plate sensor elements of 10x10x(1~2 in thickness) mm^3 (CMC sensor elements, hereafter). The addition amount of CMC in the matrix was 1-10 wt%.

The basic tactile sensing properties were measured as the following procedure: a dynamic load as well as a static load was vertically applied on the CMC sensor element using manipulator. The loaded value was measured using an electric balance on which sensor element was set. The loading speed was controlled by the motor-droved manipulator. The AC voltage of 200 KHz was applied to the sensor element through two electrodes, and the output of electric parameters of L (inductance), C (capacitance) and R (resistance) were measured using an impedance analyzer (Agilent, 4294A). Sometimes the output of electric parameters of L (inductance)+C (capacitance) and R (resistance) were transformed to a DC voltage by using a signal transformer, and the two transformed signals (L+C and R) was measured using an Oscilloscope (Agilent, 54621A).

Fig. 3 shows the typical signal output of Land C for the CMC (8wt%)/polysilicone sensor elements of $10x10x2mm^3$ under applying different loads. The load was applied for 8 sec and then released. It can be seen that the signal of LCR parameter (output voltage) steeply changed just after applied load and attained the constant value following by quick recovery to original level after releasing the load. The similar changing signal pattern of R parameter was also observed. This result shows that the CMC/

polysilicone sensor element can detect applied load by the change of electrical parameters with short response times of 0.3-0.5 s. The minimum detection limit of applied load was estimated to be several mgf orders, which corresponds to a pressure of several Pa.

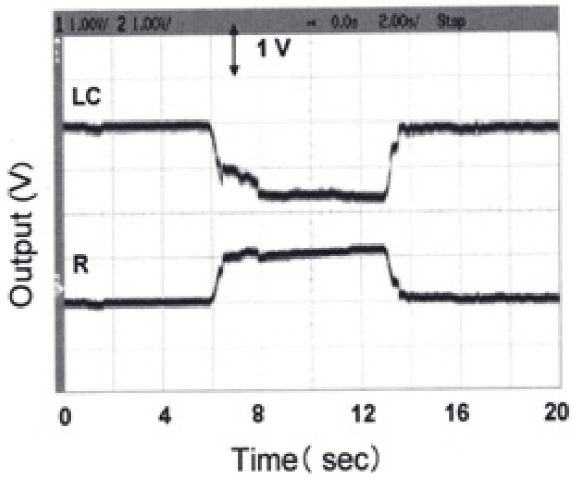

Fig. 3. Output of L+C and R parameters of CMC (8wt%)/polysilicone sensor elements. Size of element: 10x10x2 mm^3, electrodes: Cu (27x16x0.1 mm^3), Applied load: 2.0gf, separation between two electrode: 1.0 mm.

Furthermore, it has been proposed that the high sensitivity and discrimination abilities of the CMC sensor elements may be caused by a hybrid LCR (inductance, capacitance and resistivity) resonant oscillation. That is, the electromechanical properties and the resonation properties are the mechanism of the tactile sensors.

Until now, there have been three kinds of CMCs used in tactile sensors: 1) Conventional DH-CMCs: their coil gaps (i.e. the separation between coil wires) are quite small as shown in Fig. 1, the as-grown coils could be gradually extended, the coil fibers (wires) usually contact with each other (solenoid-shaped) before the extension, while they separate after the extension (to become spring-shaped), the electrical properties change with the extension or contraction (deformation); 2) Super-elastic DH-CMCs: their coil gaps are quite large, the as-grown coils could repeat extension-contraction for numberless times, the electrical properties also change with the alternating in the extension-contraction state; 3) SH-CMCs (Fig. 4).They have a largest ratio of pitch against coil diameter, the electrical properties also change dramatically with the deformation. The mechanical-electrical performance of these three kinds of CMCs is the foundation of the CMC tactile sensors. When CMCs were filled into elastic polymer to produce polymer composites, the elastic polysilicone matrix deform accompanying the deformation of CMCs and then CMCs and matrix resonate together, results in the change of electrical parameters, therefore, the composites have tactile sensing properties.

For comparing the tactile sensing properties of DH-CMC sensors and SH-CMCs sensors, we choose the resistivity as the target parameter to compare the sensitivity of the two kinds of sensor elements (Fig. 5). It can be seen that resistivity of the DH-CMC sensor is larger than that of the SH-CMC sensor. However, their resistivity decreases with the increase of the frequency in the same tendency. The typical output signals of resistivity of both sensors of 10x10x1 mm^3 CMCs (5wt%)/polysilicone sensor elements of under the different applied loads of 0.5~50 gf (gram force) is given in Fig. 5. The loads were applied for 5~8 sec and then released. In the SH-CMC elements, the output signal of the resistivity quickly decreased by the applied load and then quick recovered to the original level after releasing the load, and very large change in the resistivity; $|\Delta R| = 70$ KΩ, was obtained under the applied load of 50 gf. On the other hand, using the DH-CMC elements, a smaller signal change

|ΔR|=10.5 KΩ, and also a gradual shift in the original signal level was observed. Under the applied load of 50 gf, the value of |ΔR| was 1/7 times that of the SH-CMC elements. Furthermore, using the SH-CMCs as the sensing materials, a stable and constant original signal level could be obtained after successive extension and contraction. That is, the SH-CMC elements are more stable and sensitive than that of the DH-CMC elements. The differences in the sensing properties between the SH-CMCs and DH-CMCs elements are explained by their difference in morphology and the electromechanical performance.

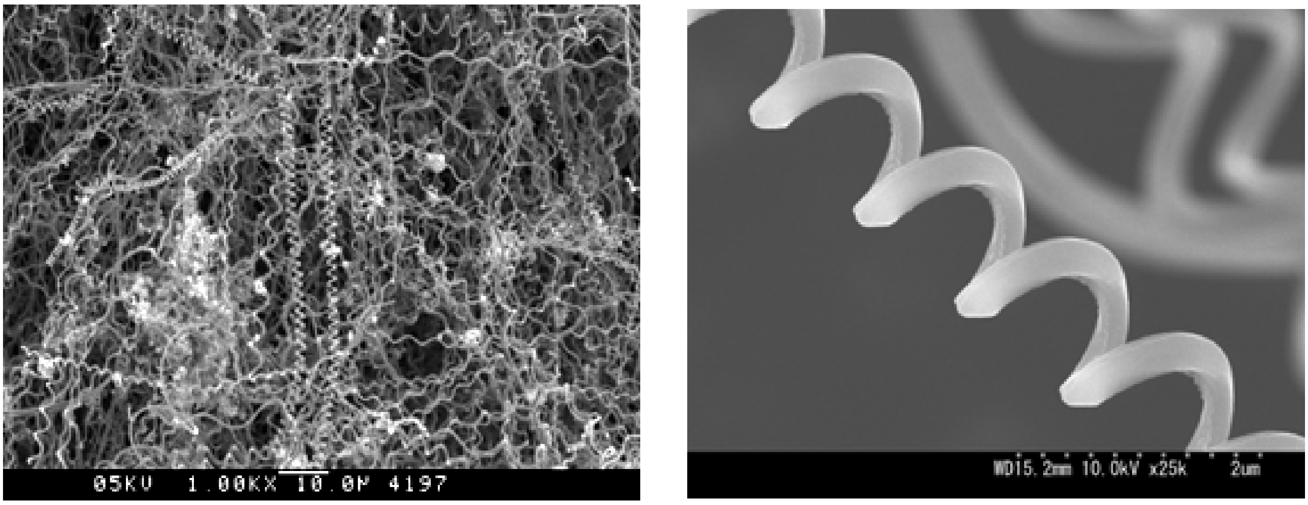

Fig. 4. The representative SEM image of spring-shaped spring-shaped single-helix carbon microcoils (SSCs) and an enlarged view.

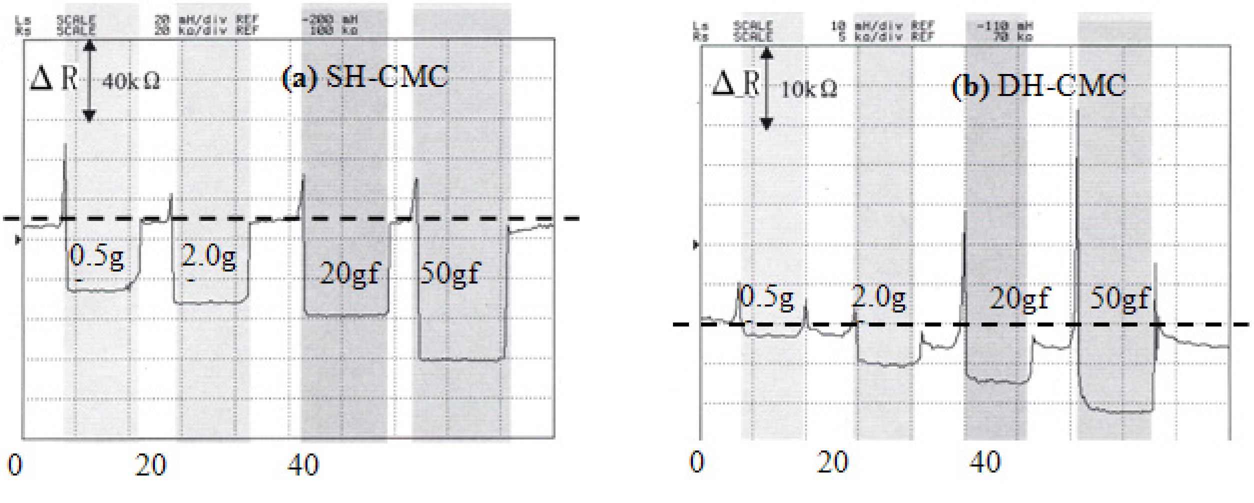

Fig. 5. Change in resistivity R (ΔR) when different loads were applied on the sensor elements during 40 seconds. (a) SHCMC sensor; (b) DHCMC sensor. Addition of CMCs: 5%. Electrodes: Au-coated Cu, 0.5 V/200KHz; Separation between the electrodes: 2.5mm.

The sensitivity of the CMC sensor element was about 1mgf, while the sensibility of conventional capacitive sensors are 13-32pF/100gf or 200-250V/100gf [11], accordingly, the CMC sensor elements have three to four orders magnitude higher sensitivity than that of conventional capacitive sensors.

4. Application of CMC Sensors

Because of the excellent properties of the CMC tactile sensors described above, the CMC tactile sensors are potential tactile sensors to overcome the shortcomings of MAS. For example, due to the high sensitivity, the CMC tactile sensors can be equipped in the half-way of the endoscope that is to say, outside the body. Thus, it can avoid the requirements concerning if the sensors are compatible to the body soft tissue organs, and body fluids or not.

An imitating apparatus for investigation of the applications of the CMC tactile sensor was designed as shown in Fig. 6. The system consists of the components imitating human organ, human body, surgery hole (key hole), an endoscope, CMC tactile sensor, endoscope assisted robot; and a balance to measure the force applied to the organ while the endoscope touch the organ.

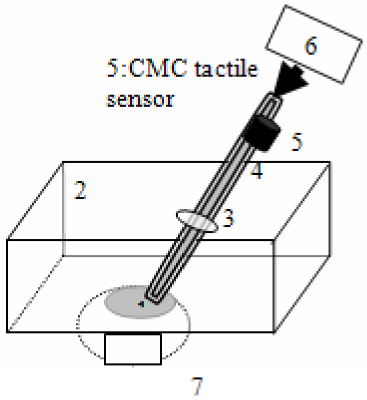

Fig. 6. A schematic figure of the apparatus mimicking the tactile sensor in MAS.
1-human organ, 2-human body, 3-surgery hole(key hole); 4-an endoscope, 5-CMC tactile sensor, 6-endoscope assisted robot; 7-balance to measure the force applied to the organ while the endoscope touch the organ.

The oscilloscope was used to measure the tactile sensing properties of the CMC sensors. When the endoscope touches the organ, results in some stresses applied to the CMC sensor elements, the LC and R components may change and modulate the applied flat signal to form some signal (output or response). The outputs produced when the sensor touch the "organ". The forces produced when the touching happened are shown in Fig. 7. A summary of the relationship between the force and the output is shown in Fig. 8. In Fig. 7, at the beginning of 15 min, the endoscope move foreword to the organ, the force increased, then, the endoscope move backward from the organ, the tactile force decreased. The change in output corresponds to the change in tactile force; they roughly have a linear relationship. However, many problems, such as reproducibility and hysteresis are under investigation.

Furthermore, CMC sensors are expected to be used in humanoid robot, in medical care as shown in Fig. 9.

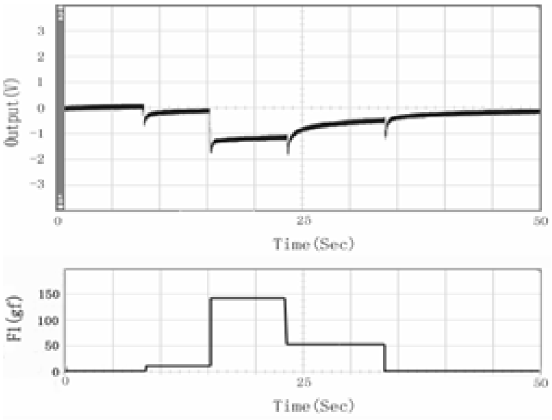

Fig. 7. The output when the sensor touches the "organ" with time flew. The force when the touch happened at (b) with time increasing.

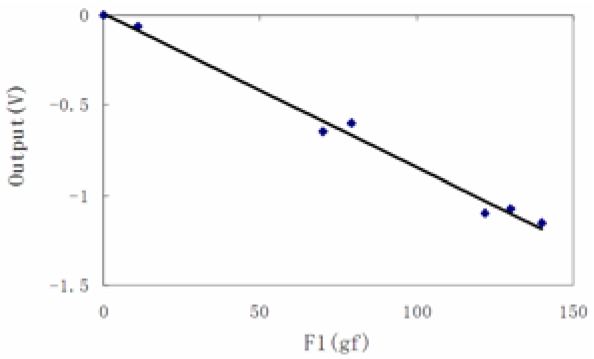

Fig. 8. A summary of the relationship before the force and the output.

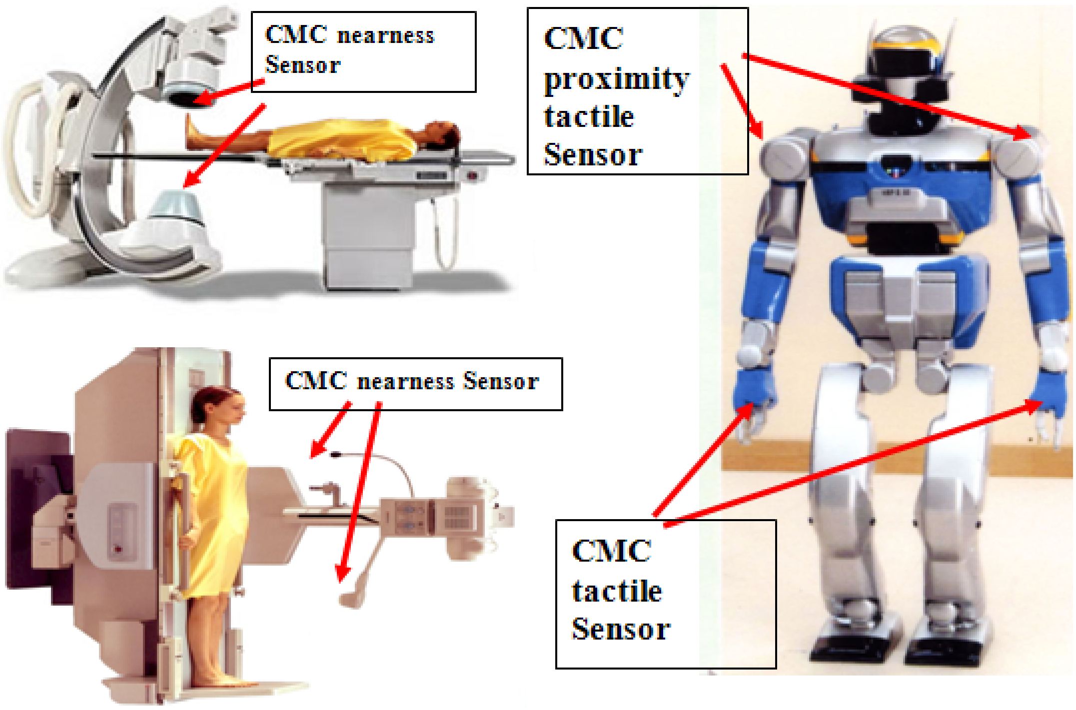

Fig. 9. Application to medical instruments or humanoid robots.

5. Conclusions

Double-helix carbon microcoils (DH-CMCs) whose morphology is similar to DNA and single-helix carbon microcoils (SH-CMCs) whose morphology is similar to proteins were prepared by Ni and Ni-alloy catalytic chemical vapor deposition respectively. These carbon materials were embedded into polysilicone matrix to form artificial skin—biomimetic tactile sensor elements and the changes in electrical parameters under the applied loads on the sensors were investigated. The comparison shows that SH-CMC sensors have higher sensibility than that of the DH-CMCs sensors. These tactile sensors have a high sensing ability to stresses and are expected to be used in minimal access surgery (MAS), in humanoid robotic, and autonomous system.

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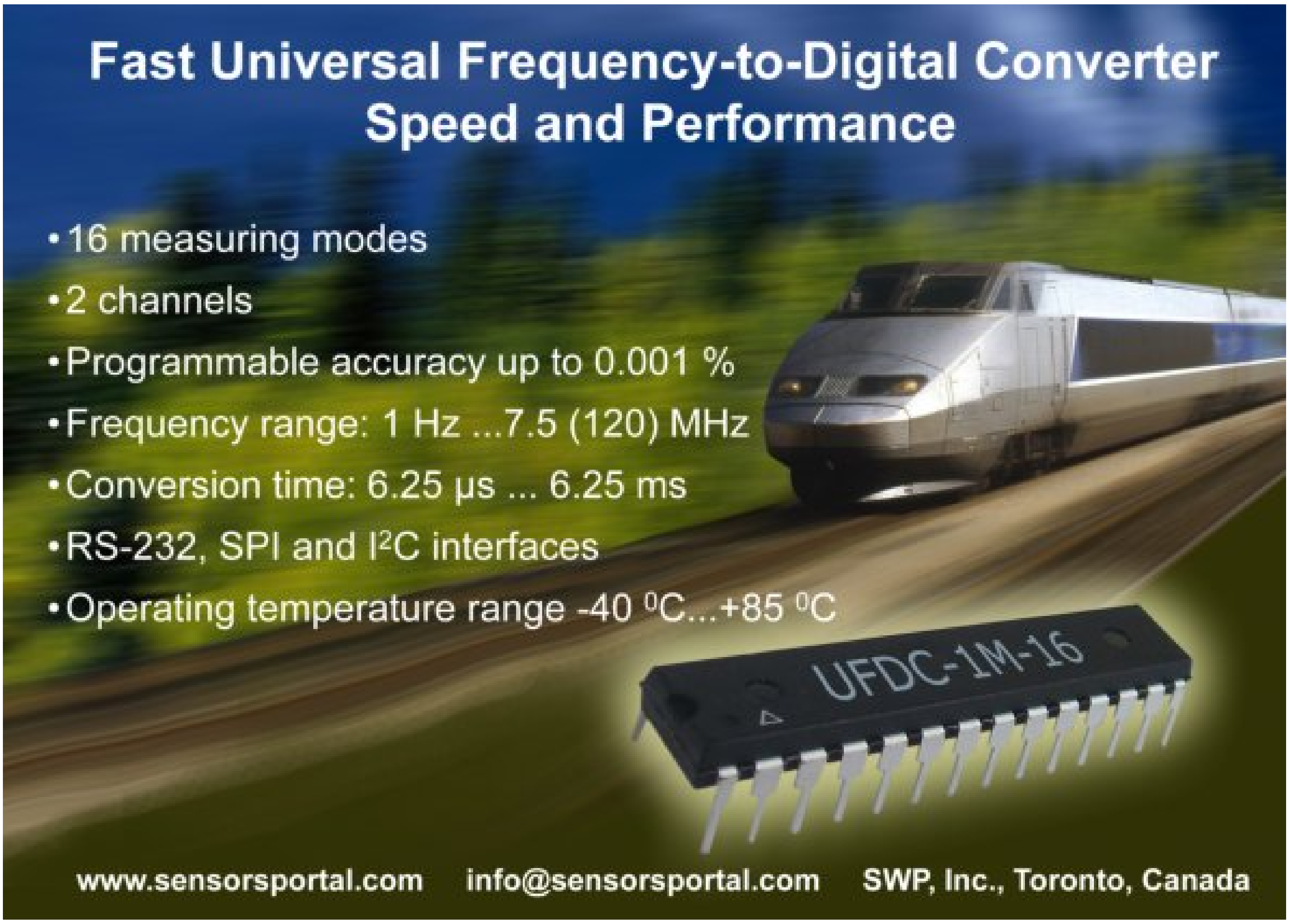

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