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Investigation of Polymer Thick-Film Piezoresistors for Medical Wrist Rehabilitation and Artificial Knee Load Sensors

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Abstract

Readily-available and low-cost commercial polymer-based composite materials, such as standard epoxy-fibreglass printed circuit board (PCB) substrates and resin-carbon thick-film piezoresistors, were evaluated as a solution for medical force sensors, such as a wrist rehabilitation device and an implantable wireless artificial knee force sensor. We show that such materials have high sensitivity, and sufficient short-term stability – provided careful mechanical design and materials selection are made - to allow fabrication of low-cost, robust sensors, with low processing temperatures compatible with electronics integration. Example load-sensing applications are a multi-axis wrist rehabilitation device and a knee prosthesis.

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Keywords: Organic thick-film material; FR4; piezoresistors; force sensor; 6 DOF

1. Introduction

There is recently a strong interest in fitting medical instruments and implants with load sensors, in order to enable robotic-assisted surgery (haptics), improve safety during operations and adjustment quality of implants such as artificial knee joints [1-4]. Instrumenting implanted devices such as fixtures (medium-term) or artificial joints (long-term) is also desirable, to monitor patient recovery and implant degradation. In the past, we have developed suitable mineral thick-film materials for firing piezoresistive load-sensing bridges on metallic substrates at temperature sufficiently low to ensure compatibility with high-strength metallic alloys such as medical-grade stainless steel, or

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even titanium [1, 4]. However, such materials still require firing temperatures around 600°C, which restricts versatility and increases costs, and contain high amounts of lead, although progress has been made towards lead-free materials, e.g. by replacement of Pb by Bi [5].

Given that most medical sensors do not require excellent long-term stability against drift; in contrast to industrial ones, loads in most applications periodically return to zero, allowing drift compensation, we endeavour to realise two force sensors based on commercial organic thick-film materials deposed on very robust glass fibre-reinforced epoxy (FR4) printed circuit boards (PCBs) as elastic substrate materials.

However, organic materials present some drawbacks: they are less stable than those based on metals and glasses, and phenomena such as signal creep are encountered and resins such as epoxy tend to pick up moisture, which also affects the resistors' characteristics. Therefore, we have studied in this work the sensitivity and the drift measured under-load and after unloading of a multi-degree of freedom (DoF) wrist force and torque sensor. A wireless knee prosthesis force sensor is also presented as a second concept of force sensor based on organic materials for medical application.

2. Experimental

Organic materials afford conveniently low processing temperatures of the order of 100-150°C, compatible with electronics that may therefore be also included directly on the PCB. In this work, for the conductors, we used a silver-epoxy glue, polymerized at 15 minutes 125°C. The commercial thick-film composite piezoresistive resistors are based on resin-carbon compositions. Both conductors and resistors were polymerized 30 minutes at 150°C.

2.1. Multi DoF wrist force and torque sensor

This sensor used for post-stroke rehabilitation exercises allow to measure 3 forces (Fx, Fy, Fz) and 3 moments (Mx, My, Mz) by combination of three sensors mechanically independent one another (Figure 1).

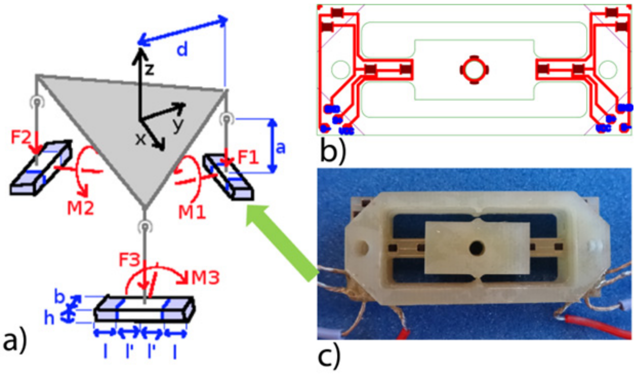

Figure 1: Multi DoF wrist sensor: a) concept, consisting of a platform resting on three identical force + torque bending sensors, b) layout of the sensing element, c) sensing beams assembled.

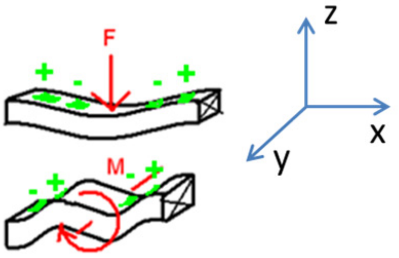

Figure 2: Force + Torque on the bridge with the signal of the piezoresistive resistors.

Each sensing element is composed of a central island linked to the frame by two beams that are (ideally) fully clamped at both sides. It nominally measures two load components: 1) the force Fz and 2) the bending torque My (Figure 2), both of which the piezoresistors in tension/compression. In contrast, a bending moment Mx or lateral force Fy shear the resistors and nominally yield no signal, which is also the case of a longitudinal force Fx (two low signals that cancel out). On each sensing element, two Wheatstone bridges have been screen-printed, with only half of the resistors active, which decreases response but allows easy separation of Fz and My by respectively adding and subtracting the bridge responses.

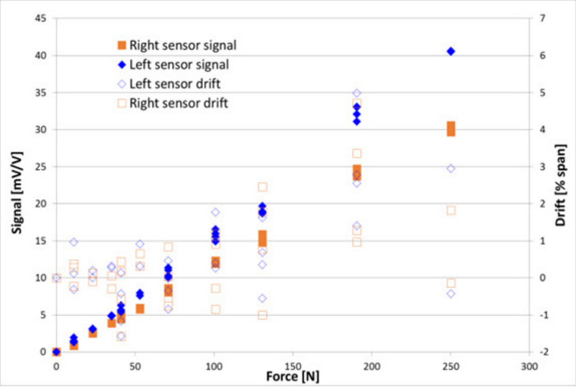

Figure 3: Signal and Drift of a sensing element with a vertical force Fz

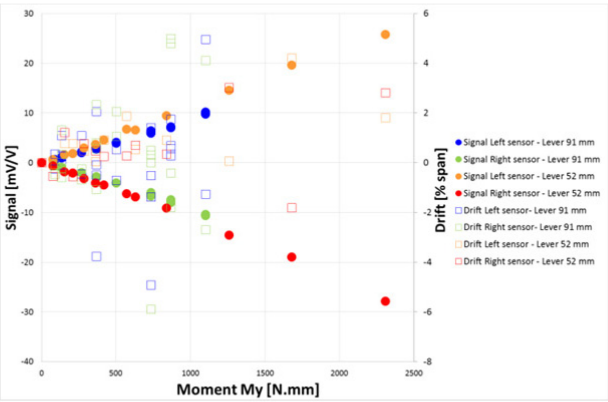

Figure 4: Torque My of the sensing element for a lever at 52 mm and 91 mm.

The signal and the drift of the single sensor with a vertical force Fz depicted on Figure 3, shows that the results are linear, very reproducible and reversible. The span at 250 N is 40mV/V for the left sensor and 30mV/V for the right sensor which is ten times higher than the signal obtained with standard alumina sensor. And the drift does not exceed 5% of the span. When the sensor is unloaded, we observed a drift due to internal stresses relaxation which will be able to solve in a next step with a better assembly. The bending torque My is represented on the Figure 4 and show the moment is linear and reproducible against the lever. The sensitivity is ~25 mV/V for a maximum torque at 2.3 N.mm for a drift is under 6 % of the maximum torque. The torsion Mx has been also measured and confirm that the signal in torsion is very low against the My torque or the force Fz since the signal of the left and right sensor are 0.3mV/V and 1mV/V at the maximal stress. Such low cross sensitivities may easily be removed by calibration.

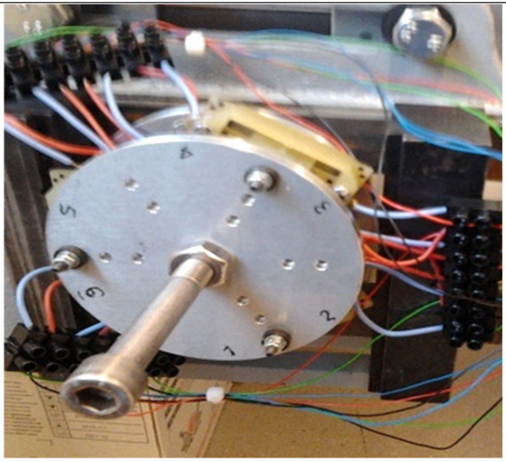

Figure 5: Multi-DoF wrist sensor on test bench.

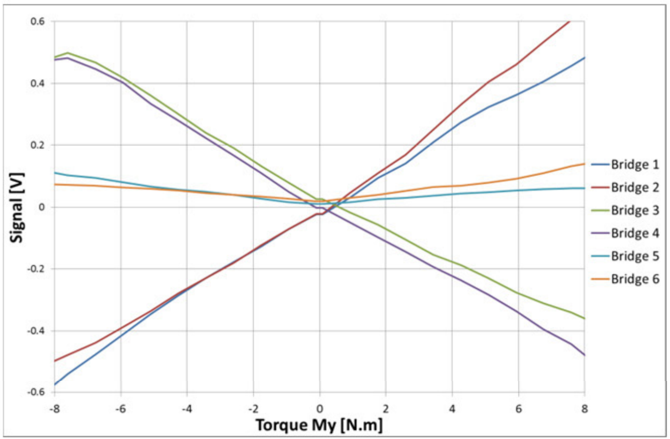

Figure 6: Signal of the 6 half bridges deposited on the three sensing elements in function of the bending torque My.

The multi DoF wrist sensor has then been tested on a test bench (Figure 5). By combination of the 3 sensors, The 3 forces and the 3 moments have been measured. In the Figure 6, an example of the response of the 6 DoF sensor towards the bending torque My. We can see that two element sensors are in flexion and in opposition direction. The third one is in torsion and then the signal is very low.

3. Wireless knee prosthesis force sensor as a second concept of force sensor

Another example of sensor based on organic thick-film piezoresistive materials for medical application is the force sensor for the total knee arthroplasty operation. A double force sensor is used in order to accurately position the implant and balance ligament tension by measuring the force applied on the two condyles (Figure 7). A sensor, composed with two sensitive membranes has been also manufactured with organic thick-film materials deposed on FR4 depicted on the Figure 8 and connected to an electronic platform for the wireless power and communications (Figure 9).

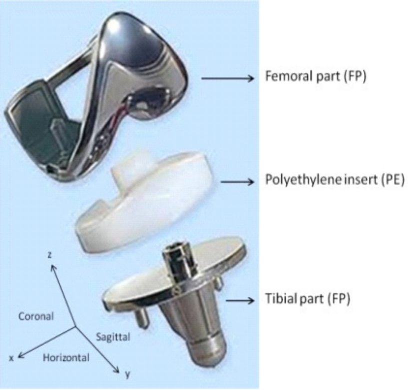

Figure 7: F.I.R.S.T knee prosthesis by Symbios SA, Switzerland.

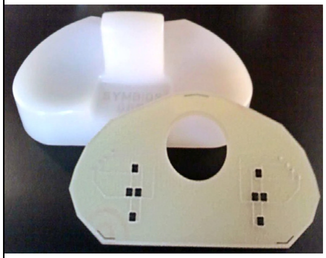

Figure 8: Sensor screen-printed with organic thick-film materials

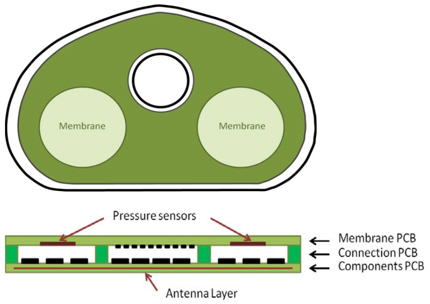

Figure 9: Concept of combined PCB for load-sensing and wireless power + communications. Placement of load-sensing membranes (top), and actual sensing element (bottom, front), with platen to apply force (bottom, back).

4. Conclusion

In this work, we have presented two very low cost medical application sensors based on organic conductors and resistors applied on FR4 PCB material. We measured that the sensitivity of these sensors is ~10 times higher than on alumina substrate and the drift of the signal is around 5% of the span. Further studies will be continued to improve the assembly of the sensors to reduce internal stresses relaxation and then minimize the drift.

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