New Generation of Optical Robotic Sensor applied to Small Notch Detection

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Abstract—**In this paper the experimental application of a new class of an optical pressure sensor based on polydimethylsiloxane (PDMS)-Au is shown. The sensor consists of a tapered bended optical fiber, where an optical signal goes across, embedded into a PDMS–gold nanocomposite material (GNM) and it is used for scanning surfaces while it is moved automatically by a controlled servomotor. The sensor data during the scanning may be used for detecting a small notch on a beam. The experimental results are very encouraging for foreseeing successful use of this new sensor in robotic applications.**

Keywords-component; mechatronics device, light coupling, nanocomposite materials, optical tactile sensors, pressure sensing, robotic implementation.

I. INTRODUCTION

SENSORY information of the human skin for feeling materials and determining their physical properties is provided by sensors on the skin. In particular, many kinds of tactile sensors, combining small force sensors, have been introduced into intelligent robots. These tactile sensors, which are capable of detecting contact force, vibration, texture, and temperature, can be recognized as the next generation of an information collecting system. The proposed optical fiber sensor is obtained by means of a simple fabrication process: a used nanocomposite material, which the fiber is embedded in, is achieved simply by chemical reduction that allows to obtain nano/micro gold particles in a polymericmaterial [i.e., a gold nanocomposite material (GNM)].

The use of elastomers such as polydimethylsiloxane (PDMS) has many advantages with respect to silicon or glass. PDMS is cheaper than silicon, is more flexible, and bonds easier to other materials than silicon or/and glass. PDMS conforms to the surface of a substrate over a large area and can adjust to surfaces that are non-planar. The GNM supports light coupling with a tapered multimodal optical fiber and does not require complex layouts, such as membrane-type devices obtained by photolithography processes. The information of pressure detection is included in a optical transmittivity response, which decreases by applying pressure forces. Transmitting intensity can be detected and directly converted into an electrical signal by a photodiode and processed by a proper electronic circuit suitable for robotic implementation. The sensor reported is an optimized version obtained after previous preliminary studies [1].

II. TACTILE SENSOR: TECHNOLOGICAL ASPECTS AND BASIC PRINCIPLES

The sensor illustrated in Fig. 1 (a)-(c) [2] and in Fig. 2 is obtained after previous preliminary studies [2-3]: in the optimized version of the sensor the whole diameter of the tapered fiber is embedded in the GNM thus increasing the sensor sensitivity. An optical ray coming from a broad lamp source is dispersed inside the gold nanocomposite material when the sensor is pressed on a surface: this effect is due to the electromagnetic coupling of the tapered fiber with the PDMS-Au material which provides a reduction of the transmitted signal. The gold nanoparticles formed in the PDMS material are expected to increase the effective refractive index of the PDMS and support the electromagnetic coupling with the tapered region of the fiber, since the transmitted light tends to preferentially propagate into the high refractive index regions. The pressure applied on the GNM introduces a displacement of the nanoparticles along its interface with the tapered fiber increasing the light scattering [2-3] (see Fig. 1 (b)): the nanoparticles thus increase the coupling of light with the GNM, reducing the transmitted light intensity of the optical fiber. Regarding the modifications of the optical properties of the GNM, the effect of the nanoparticles displacements due to the applied pressure is to change the effective refractive index of GNM as a function of gold concentration. In particular the gradual variation of the GNM effective refractive index is higher near the contact interface of the tapered fiber, and, lower towards the pressure contact surface. We can model the gradual variation of the GNM effective refractive index as illustrated in Fig. 1 (a)-(c), where the region with higher refractive index is near the contact interface of the tapered fiber, and, the region with lower effective refractive index is towards the pressure contact surface. This variation of the effective refractive index can be approximately estimated assuming spherical gold nanoparticles in Polydimethylsiloxane (PDMS) material. In this case the effective dielectric function ε_{eff} for spherical gold particles having dielectric function ε_m which varies with the optical working wavelengths [2-3], embedded in a medium ε_s is defined by [4]-[5] as:

$$\varepsilon_{eff} = \varepsilon_s \frac{\varepsilon_m(1+2\phi)+2\varepsilon_s(1-\phi)}{\varepsilon_m(1-\phi)+\varepsilon_s(2+\phi)}. \quad (1)$$

where ϕ indicates the gold concentration.

The modes of the tapered fiber will exchange the power with PDMS-Au cladding by defining the coupling coefficient as follow [6]

$$C_{\psi_{nm},E^r}(z) = \omega \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta\varepsilon_{eff}(z)\psi_{nm}E^r dxdy \quad (2)$$

where ψ_{nm} are the fiber modes, E^r is the electric evanescent field radiated by the tapered profile, and $\Delta\varepsilon_{eff}$ indicates the variation of the effective permittivity of the cladding due to different applied forces. According with (2), we observe that the coupling can be increased by bending the tapered fiber as shown in Fig. 1 (a) and (b).

The proposed prototype sensor layout illustrated in Fig. 1 (a) consists of a tapered multimode Si fiber which couples the electromagnetic field coming from a broad band lamp source with the flexible polymer-gold nanocomposite material (GNM). The GNM material (PDMS-Au) is fabricated by PDMS polymer film due to its ability to generate gold nanoparticles starting from gold precursors [7]-[8-9]. The sensor are designed in order to improve a high sensitivity for low applied pressure forces: the design considers the double radiation effect due to the bending loss effect and to the radiation of the tapered profile [10].

By this double effect we will obtain high coupling coefficients (2) due to the high intensive evanescent E^r fields, and, consecutively, high sensor sensitivities. Moreover, we consider a multimode optical because it is characterized by a core diameter big if compared by the diameters of the single mode fibers: in this case more contact interface will increase the coupling efficiency.

The sensor prototype of Fig. 1 exhibits a very high sensitivity. We have designed the sensor layout of Fig. 1 by means of a cylindrical PVC support in order to improve a major mechanical stability and a good adhesion. The optical fiber is passed through two external holes (see Fig. 1 (b)), and a glue is added in these external holes in order to fix the fiber. The PVC support allows to fix the optimum radius of curvature of the fiber for the tapered process (heating controlled system). In the table I are reported the data-sheet of the sensor and the optical and electronic approaches used for the measurements.

TABLE I. SENSOR CHARACTERISTICS

	Prototype
Chemical composition of GNM	PDMS + gold precursors (concentration of 4% in weight)
Order of Sensitivity	≅5 grams of equivalent applied pressure
Elastomeric GNM time response at 0.098 N (≅10 grams)	≅ 0.6 sec
Optical Experimental setup	Sensor + photodiode + numerical oscilloscope
Photo detector	Thorlabs DET 36 AIM Si based Detector
Optical source	MIKROPACK HALOGEN LIGHT SOURCE HL-2000-FHSA
Electronic Analyzer	TEKTRONIX TDS 200
Type of analysis	Electric signal processing (electric characterization); sensitivity versus the apertures
Optical fiber	FT200EMT Thorlabs

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III. TACTILE SENSOR: APPLICATION FOR DETECTING A SMALL NOTCH ON A BEAM

The tactile sensor has been used for detecting a small notch on a beam by means of a scanning of the beam surface. At this aim the tactile sensor has been linked on a controlled servomotor with small plates screwed on a plastic support in such a way that it can rotate on a plane adjacent to the beam surface (Fig. 3). The device is moved by a digital motor (digital AX-12+ Dynamixel) having the rotating shaft connected to the plastic support where the tactile sensor is linked. The digital motor is driven through a serial port by a USB2Dynamixel connector and its rotation may be controlled with high precision. Consequently the tactile sensor may scan a certain part of the beam acquiring, for each position, information about the pressure.

A. Experimental test results

The characterization results [1] of the sensor prototype showing voltage reduction with small weights (order of grams) hanged up to the tapered fiber, suggest the authors to test the sensor for scanning a beam with a very small notch compared to the sensor diameter (around 1.5 cm).

An angular rotation $\Delta\theta$ of 1° was fixed for the motor axis rotation while the sensor scanned the beam starting from a position where the notch was external to the sensor (Fig. 4 (a)) and finishing when the notch was again external but after being completely scanned by the device (Fig. 4 (b)). The sensor is lightly pressed on the beam surface and a preliminary test was carried out for verifying the correct alignment for all the scanning positions.

The movement of the sensor (Fig. 5 (a)) is generally described by a circumference arc, but, in this case, the opportune long arm used (about 9 cm) and the small angular rotation considered, permit to approximate the sensor movement with a segment (Fig. 5(b)). In this way the scanning movement may be considered linear and it is assumed to be perfectly aligned with the scanned surface.

For each position the data of the sensor are saved using the electronic analyzer (sampling time 0.00004 s, 2482 samples acquired in 0.0992 seconds) after a delay time bigger than the mechanical sensor elastomeric response (≅ 0.6 sec) and then analyzed checking the signal statistical proprieties in each position and, finally, the voltage trend in the different positions.

In this work we show the preliminary encouraging results referred to the scanning of a notch of 3 mm and depth 1 mm (shown in Figs. 3 and 4 (a) and (b)) in Table II and Fig. 6. It is evident from Table II the excellent repeatability of the voltage signal of the prototype sensor, that almost constant in each position because it has a very low standard deviation during the whole acquisition time. In addition, considering the trend shown in Fig. 6 where are plotted the mean values in each position, it is evident that the sensor detects the notch with a variation of the signal value. The result is very important considering the extremely small dimension of the notch, that could be detected only with extreme difficulties or could not be detected at all with the classical non-destructive detection methods (i.e. modal analysis, ultrasounds, digital image correlation); this preliminary tests confirm the characterization data shown in [1] and the sensitivity of the new sensor to very low variation of pressure.

TABLE II. EXPERIMENTAL RESULTS

Position [°]	Mean value [V]	Standard deviation
0	1.7913	0.0011
1	1.7911	0.0011
2	1.7921	0.0009
3	1.7931	0.0012
4	1.7954	0.0011
5	1.7962	0.0009
6	1.7964	0.0010
7	1.7863	0.0010
8	1.7879	0.0012
9	1.7910	0.00108

IV. CONCLUSION

For the first time we have applied the innovative GNM pressure sensor to detect millimeter notches. These preliminary results are promising for a possible implementation in a robotic system including approaches for the mechanical alignment during the scanning process. The same proposed sensor can be implemented in mechatronic systems able to detect cracks in pipeline or damages of material. The new material used for sensing represents a new generation of pressure sensors suitable for light contacting pressure. Actually we are developing controlled automatic approaches in order to detect smaller notches and to define criteria of measurements for these kind of sensors. The studies are oriented in order to define the limits of the mechanical handling accuracy. A good matching between the optical signal detection and the mechanical handling has been achieved for carrying the results here shown.

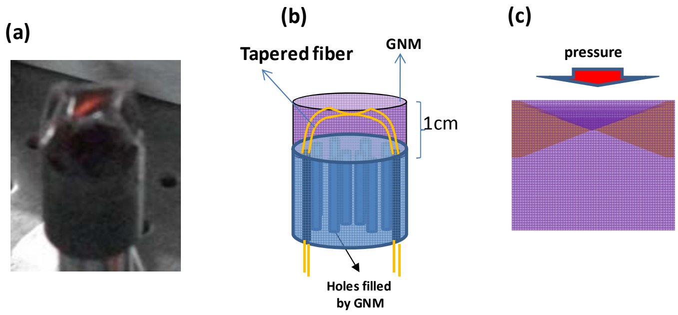
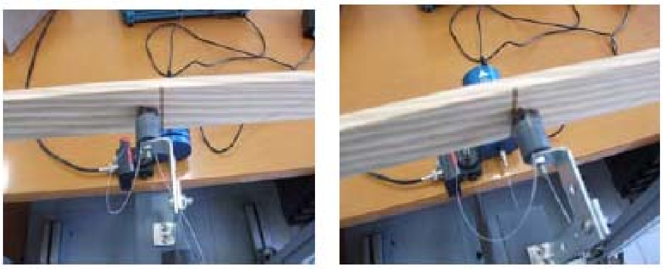


Figure 1. – (a) Sensor prototype. (b) Sensor layout. (c) Schematic sketch of the pressure effect: equivalent GNM as gradual variation of the effective refractive index.

Figure 2. Details of the sensor used.

Figure 3. Sensor mechanical handling.



(a) (b)

Figure 4. a) Starting position of the scanning test, b) End position of the test

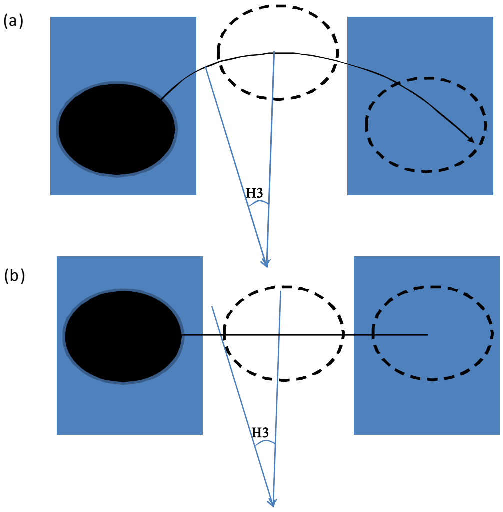


Figure 5. a) Scanning rotation, b) Scanning approximation for the test

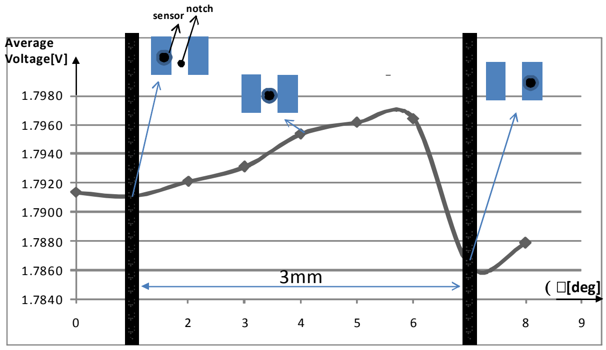


Figure 6. Scanning experimental results

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