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# Strange Attractors and Nonlinear Devices for New Class of Sensors

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**Abstract**—Post-silicon materials like polymers and solution-based devices allow to design new types of selective sensors. On the other hand, the nonlinear dynamic behavior of a class of nonlinear circuits offers the possibility of conceiving devices where the nonlinearity of the circuit is exploited to realize new mechanisms or improve classical ones. In this paper we discuss the possibility of coupling a new class of materials with nonlinear dynamic circuits to design a new class of selective sensors. The results that are included are preliminary and cover a wide range of applications. Moreover, several experimental results show the possibility of conceiving new multifunctional low-cost and eco-compatible sensors.

## 1. Introduction

In this paper some qualitative preliminary results on a new class of a sensors [1] whose core principle is based on the nonlinear dynamics of a class of electronic circuits are presented. In particular, polymeric materials have been considered. Our study is focused on the use of clevios-based sensors, Ionic Polymer Metal Composites (IPMCs), and solution-based systems to detect various physical quantities like movements, humidity, concentrations and so on. The idea is to use the material as the electrical transducer and insert the electrical transducer into a nonlinear circuit. The effect of the coupling of these components with a nonlinear circuit like the Chua's circuit is that a variation of the dynamical attractor will be obtained as result of the change of the quantity to which the material is sensible. Chaos has been already demonstrated to be helpful to improve the performance of sensors and other equipments, such as sonar sensors, mechanical systems and other devices [2, 3]: in this work, detection of the given quantity is made possible by the extreme sensitivity of the circuit to the variations of its parameters. In this study selective sensors based on water solutions, that have a behavior assimilable to RC components with frequency dependent values and so are difficult to realize with classical components, are also reported.

The paper is organized as follows. In Section II the sensor devices are described. The coupling of this type of devices with nonlinear circuit is introduced in Section III. A gallery of qualitative experiments are outlined in Section IV. In Section V some conclusive remarks are given. The sensor characterization will be the subject of a future research.

## 2. Sensor components

In this Section three types of sensors are discussed. The first one regards the clevios based sensors. Clevios is a conductive polymer. The clevios used (clevios-P HCV4) is commercially available in a water colloidal suspension. A layer of thickness of $100\mu m$ is coated on a surface and then treated in an oven at $80°C$ for 50 min. Two different supports have been used: a glass support and a PVC foil. The first may be used to realize humidity, wet and PH sensors as the resistivity of clevios based materials is sensitive to these quantities. The second type of device (those were the clevios is coated on flexible PVC foil) may be used to detect movements. In this case, the clevios-based sensor is considered as an electrical bipole whose resistivity depends on the surface deformation.

The second type of sensor is realized by using Ionic Polymer Metal Composites (IPMCs). These materials belong to the class of wet electro-active polymers. They are made of an ionic polymer membrane covered on both sides with Platinum, which realizes the two electrodes of the device. IPMCs operate with low-voltage signals, are very light, and have both actuator and sensor characteristics. They are used after being cut in strips. If an electric field is applied across the thickness of a strip, it undergoes an ample bending deformation. Viceversa, by bending a strip of IPMC, a voltage arises between the two metallic electrodes. Hence, IPMCs can operate as motion actuators or sensors. Instead, in this work, we exploit the dependence of the resistivity of IPMC on the hydration of the membrane to realize a humidity sensor.

The last device used is based on the resistivity change of a water solution. The device consists of four copper filaments on a plexiglass substrate which are electrically connected in two pairs (the two top ones and the two bottom ones). The space between the filaments hosts a small quantity of a water solution so that the value of the resistance measured at the two terminals of the device is made dependent on the quantity of water.

The various components are shown in Fig. 1. Fig. 1(a) shows the first clevios-based device. It is realized on a rigid glass support, the sensor area has

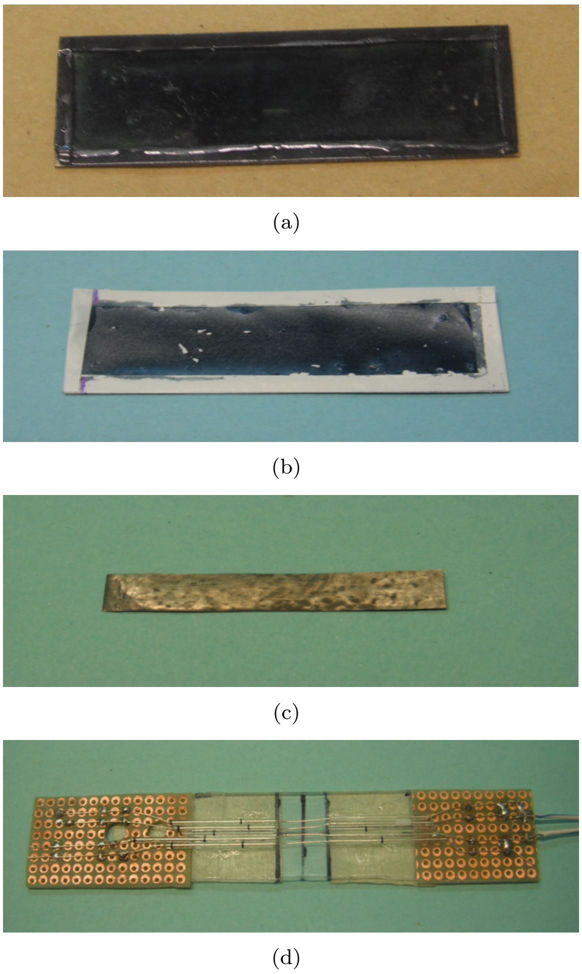

Figure 1: Pictures of the sensors: (a) the clevios-based sensor (glass support); (b) the clevios-based sensor (PVC support); (c) IPMC sensor; (d) water solution-based sensor.

a length equal to $70mm$ and width equal to $20mm$. Fig. 1(b) shows the second clevios-based device. This is realized on a PVC (3M Temflex 1500) of thickness equal to $0.3mm$. The active area of the sensor measures $55mm \times 15mm$. Fig. 1(c) shows the IPMC strip used. The size is $44mm \times 9mm$. The IPMC material has been realized with the procedure detailed in [4]. Fig. 1(d) shows the last device. It is realized by fixing four copper wires on a plexigas support (of thickness $2mm$). Each wire has diameter equal to $0.22mm$. The distance between each pair of wires is $1.5mm$. The wires are isolated by glass microtubules with the only exception of a window of $10mm$ of length which constitutes the active area of the sensor.

## 3. Nonlinear circuits and sensors

In this Section we briefly describe some experiments to show the proof of concept of the coupling of new materials and nonlinear circuits. As discussed in Section II all the devices illustrated can be viewed as two-terminals devices. The principle with which they have been coupled to the nonlinear circuit is common for all the devices. Starting from the Chua's circuit [5], we identify one resistor of the circuit as the bifurcation parameter. In particular, without any loss of generality, we have taken into account the so-called CNN-based implementation of the Chua's circuit [6], whose electrical scheme is shown in Fig. 2, and identified as bifurcation parameter the resistor $R_6$.

The circuit obeys to the dimensionless equations:

$$\begin{aligned} \dot{x} &= \alpha[y - h(x)] \\ \dot{y} &= x - y + z \\ \dot{z} &= -\beta y \end{aligned} \tag{1}$$

with $h(x) = m_1 x + 0.5(m_0 - m_1)(|x+1| - |x-1|)$ and $x = x_1/1V$, $y = x_2/1V$, $z = x_3/1V$ being the state variables. For sake of brevity, we refer to [6] for a more detailed discussion on the Chua's circuit and on the CNN-based implementation reported in Fig. 2. Here, we briefly mention that $\alpha$ is a key bifurcation parameter and it is related to the component values by $\alpha = \frac{R_5 R_{18}}{R_3 R_6}$. We have thus kept constant $R_3$, $R_5$ and $R_{18}$ and in place of resistor $R_6$, we have connected each of the sensors described in Section II.

In some cases, where the typical values of resistance given by the device are out of the range of the operating conditions of the Chua's circuit, a resistor, indicated in the following as $R_p$, has been also connected in parallel to the device terminals. We notice that the approach presented may be applied also to other resistors of the circuit, selected on the basis of the sensitivity of the behavior with respect to them.

The first experiment refers to the use of the clevios-based sensor of Fig. 1(a). This is a sensor realized by coating the clevios on a rigid support. The two terminals of this device have been connected to the Chua's circuit and the experimentally obtained attractors for two different operating conditions of the sensor have been reported in Fig. 3. Fig. 3(a) shows the sensor where a dry finger has been applied in the active area. The corresponding attractor is shown in Fig. 3(b). It is the well-known Chua's double scroll attractor. When a wet finger is applied to the sensor, as in Fig. 3(c), the attractor in Fig. 3(d), that is, the so-called single scroll attractor, is obtained.

The different dynamical behavior obtained allow to easily distinguish the different operating conditions of the sensor. The value of the resistance of the clevios-based sensor in dry conditions is $97k\Omega$, this is outside the typical range of values used for $R_6$ in the Chua's circuit. Therefore, in this experiment, a parallel resistor of value equal to $R_p = 375\Omega$ has been used.

In the second experiment the sensor based on clevios deposition on a flexible support is considered. The ex-

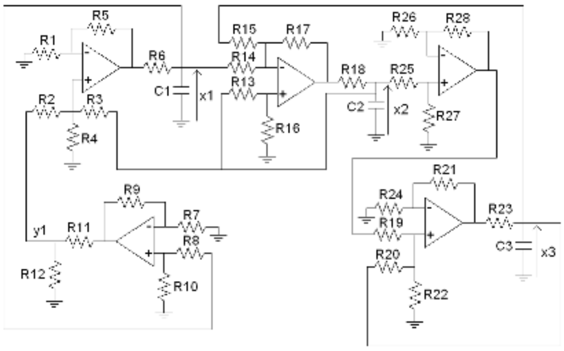

Figure 2: Electrical scheme of the CNN-based implementation of the Chua's circuit. The following components have been used: $R_1 = 4k\Omega$, $R_2 = 13.3k\Omega$, $R_3 = 5.6k\Omega$, $R_4 = 20k\Omega$, $R_5 = 20k\Omega$, $R_6$ fixed from experiment to experiment as the sensor device, $R_7 = 112k\Omega$, $R_8 = 112k\Omega$, $R_9 = 1M\Omega$, $R_{10} = 1M\Omega$, $R_{11} = 12.1k\Omega$, $R_{12} = 1k\Omega$, $R_{13} = 51.1k\Omega$, $R_{14} = 100k\Omega$, $R_{15} = 100k\Omega$, $R_{16} = 100k\Omega$, $R_{17} = 100k\Omega$, $R_{18} = 1k\Omega$, $R_{19} = 8.2k\Omega$, $R_{20} = 100k\Omega$, $R_{21} = 100k\Omega$, $R_{22} = 7.8k\Omega$, $R_{23} = 1k\Omega$, $C_1 = C_2 = C_3 = 100nF$. The power supply has been fixed to $\pm 9V$.

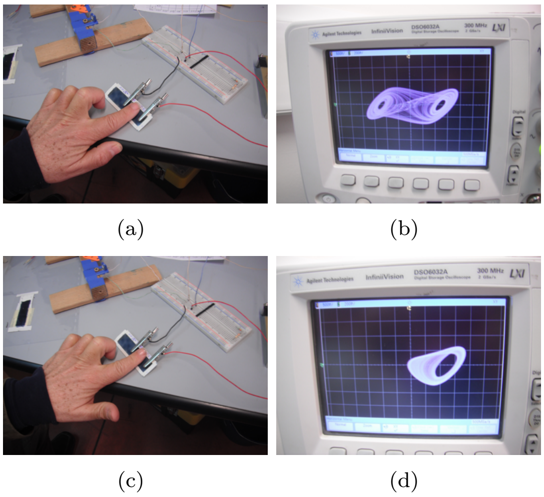
(a) (b) (c) (d)

Figure 3: Wet detection experiment. (a) A dry finger is applied to the sensor. (b) Attractor corresponding to the experimental condition of dry finger. (c) A wet finger is applied to the sensor. (d) Attractor corresponding to the experimental condition of wet finger.

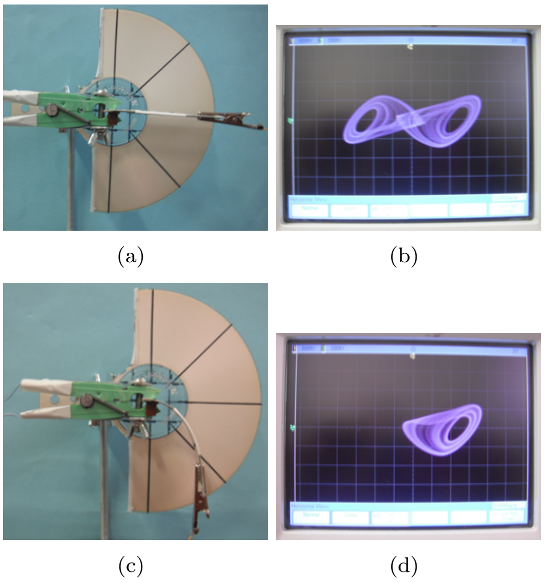
(a) (b) (c) (d)

Figure 4: Deformation detection experiment. (a) Clevios-based sensor in the horizontal position. (b) Attractor corresponding to the experimental condition of horizontal position. (c) Deformed position for the clevios-based sensor. (d) Attractor corresponding to the experimental condition of deformed clevios-based sensor.

periment is illustrated in Fig. 4. When the sensor is in the horizontal position (Fig. 4(a)), the attractor obtained is the Chua's double scroll attractor (Fig. 4(b)). In correspondence of a bending with an angle of $\pi/4$ (Fig. 4(c)), the Chua's single scroll attractor is obtained (Fig. 4(d)). In this experiment $R_p$ has been fixed as $R_p = 447\Omega$. The resistance of the clevios device changes from $4965\Omega$ in the horizontal position to $5530\Omega$ when bended.

The experiment based on the use of an IPMC strip is illustrated in Fig. 5, through different frames of a video recording the attractor obtained on the oscilloscope. At time $t = 0$ (Fig. 5(a)) a limit cycle periodic attractor is evident. When the IPMC membrane is hydrated by inserting it in a small container filled of water (this takes a few seconds after the beginning of the recording), the attractor changes. Due to the presence of equivalent resistive and capacitive effects in the membrane, a switching dynamics emerges. The dynamics is characterized by oscillations which spiral towards one of the two unstable equilibrium points of the circuit. Before reaching the equilibrium, the trajectory suddenly jumps to the other lobe and starts again spiralling, this time towards the other equilibrium. This repeats until the membrane becomes again wet. In Fig. 5(b)-(f) we show the trajectory observed in the oscilloscope up to 3 minutes after the hydratation. The phenomenon maintains for about 15 minutes. In this

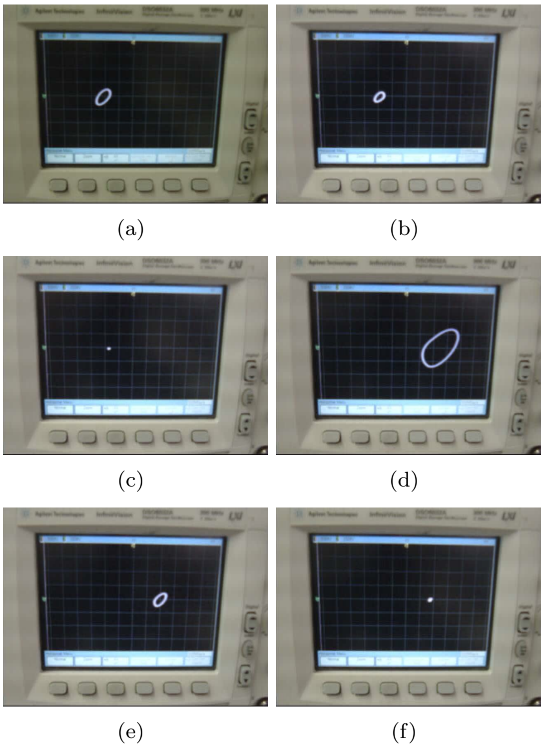
(a) (b) (c) (d) (e) (f)

Figure 5: IPMC hydratation sensor experiment. (a) $t = 0s$; (b) $t = 60s$; (c) $t = 105s$; (d) $t = 120s$; (e) $t = 150s$; (f) $t = 180s$.

experiment $R_p$ has been fixed to $R_p = 413\Omega$.

In the fourth experiment the sensor shown in Fig. 1(d) is used. It has been directly substituted to the $R_6$ resistor without inserting further parallel resistor. When the sensing area is dry, the attractor is a stable equilibrium point (Fig. 6(a)). On the contrary, when a small quantity of water (or even a wet finger) is placed in the active area of the sensor, the circuit starts to oscillate as shown in Fig. 6(b).

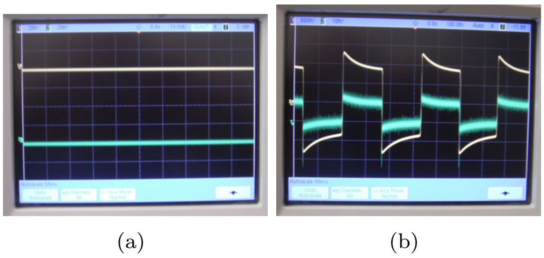
(a) (b)

Figure 6: Experiment based on the sensor of Fig. 1(d): (a) attractor obtained for an experimental dry condition; (b) waveforms corresponding to wet experimental conditions.

## 4. Conclusion

In this work the coupling between new materials and nonlinear circuits has been explored to design a new class of sensors. The principle is to link the variation of a quantity detected by the material to the change of a parameter of a chaotic circuit, so that to exploit the parameter sensitivity of chaotic circuits. A proof of concept has been given in this work, by using different types of innovative materials/devices, such as clevios, IPMC and water solution cells. The principle has been demonstrated with a series of experiments that pave the way to a more intensive characterization of the devices proposed. The variation of quantities such as humidity, hydratation level or bending has been here shown to lead to significant changes in the dynamical behaviors of the circuit (in particular, a Chua's circuit has been used), that is, the dynamical behavior of the nonlinear system bifurcates as a result of the sensing. Although the principle may be applied to a variety of materials, it is particularly interesting when applied to newly conceived materials which as such may be at a preliminary stage of development or characterization, yet they can be successfully used with such approach.

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