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Article

Novel Impedance Sensor based on the Chaotic Van der Pol and Damped Duffing Circuits Coupled

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Abstract: The signature of chaotic systems can be characterized either by the sensitivity of the initial conditions or by the change of its parameters. This feature can be used for manufacturing high sensitivity sensors. Sensors based on chaotic circuits have already been used for measuring water salinity, inductive effects, and both noise and weak signals. This article investigates an impedance sensor based on the Van der Pol and Duffing damped oscillators. The calibration process is a key point and therefore the folding behavior of signal periods was also explored. A sensitivity of 0.15 $k\Omega/Period$ was estimated over a range from 89.5 to 91.6 $k\Omega$. This range can be adjusted according to the application by varying the gain of the operational amplifier used in this implementation. The development of this type of sensor might be used in medical and biological engineering for skin impedance measurements, for example. This type of chaotic sensor has the advantage of sensing small disturbances and then detect small impedance changes within biological materials which, in turn, may not be possible with other detectors.

Keywords: Impedance Sensor, Chaotic Oscillator, Van der Pol, Damped Duffing Circuit.

1. Introduction

Many experiments in the biological, engineering and physical sciences have shown that a fundamental implicit property of chaos is a sensitive dependence on the initial conditions. According to [1][2], the change in state of a dynamic non-linear system that can be obtained through small changes in the system parameters is also the result of a sensitive dependence on the initial conditions. Therefore, the parameter's sensitive depend on the initial conditions. These properties could significantly improve the characteristics of various types of sensory systems. The hypothesis of chaotic sensors is that weak changes in system parameters can cause significant changes in its behavior, in contrast to linear oscillators in which small changes in parameters only cause small changes in oscillation dynamics [3]. For this reason, sensors based on chaotic circuits have been increasingly studied and used in the sensing area, among some examples, this approach has been used to determine the salinity of water [4], also on inductive sensors [3], noise-activated non-linear sensors [5][6][7], weak signal detection sensors [8][9] and impedance sensors [10]. There are several ways to implement a chaotic circuit for sensing, in [5] a description of the system dynamics is discussed, which allows for the use of a measurement technique based on the monitoring of the permanence time of the system in its stationary states. And in [1] three different case studies are presented that explore the sensitivity dependence on the initial conditions to build a sensory device that can be implemented in hardware. One of the experiments uses the control manifold theory to build a sensor that uses the change in the character of a fixed point from elliptical to hyperbolic as a detection mechanism. A second experiment uses the escape from the basin of attraction from a fixed point as a detection mechanism. And a third one uses a bifurcation process to obtain a change of state in a duplication oscillator. The bifurcation theory studies and classifies phenomena characterized by sudden changes

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in behavior resulting from small variations in the imposed conditions, analyzing how the qualitative nature of the equations solutions depends on system parameters [11]. In a system of equations dependent on parameters, the qualitative structure of the flow can change by varying its parameters. In order to better understand these dynamic changes, it is necessary to briefly define what period, equilibrium point and chaos is within the context of nonlinear dynamics. Period in nonlinear dynamics and chaos theory means that the chaotic system can have sequences of values for the evolving of variables that are repeated at a regular interval, providing periodic behavior from any point in that sequence. The equilibrium point would be the condition in which the system is characterized by a single point in the phase space and chaos when the system shows chaotic behavior in that same phase space [12]. In particular, equilibrium points can be created or destroyed, or have their stability altered. These qualitative changes in dynamics are called bifurcations and the parameter values in which they occur are called bifurcation points. In other words, bifurcation is a change in the topological type of the system when its parameters pass through a critical value. Bifurcations are scientifically important, as they provide models of transitions and instabilities when some parameters are varied [11]. There are some types of bifurcation in continuous dynamic systems, in which equilibrium points can be created or destroyed, or have their stability altered by varying one or more parameters [13]. In continuous dynamic systems, there are two main bifurcations by which an equilibrium has its stability altered by varying one or more parameters: the saddle-node bifurcation and the Hopf bifurcation. The saddle-node bifurcation is the basic mechanism for creating and destroying equilibrium points, and is also called the fold, tangent, limit point or return point bifurcation. The Hopf bifurcation of a system implies in the generation of a limit cycle. If a Hopf bifurcation grows by adequately varying the system parameters, it can generate a periodic limit or attractor cycle. In addition to the equilibrium, the most common form of behavior is a limit cycle. A limit cycle is an isolated closed path, isolated in the sense that neighboring paths are not closed, so they spiral towards or away from the limit cycle. Stable limit cycles are very scientifically important, as they model systems that exhibit self-sustaining oscillations. In other words, these systems oscillate even without periodic external forces. One of the possible bifurcations of a limit cycle generated by Hopf bifurcation is the period doubling bifurcation. The original limit cycle becomes unstable as a family of duplicate period solutions emerges. In general, a series of n duplications may arise after each $2^n T$ period limit cycle is obtained. Several systems have an infinite series of bifurcations with a finite accumulation point; the associated movement beyond that point is chaotic, characterizing a route to chaos via a period doubling or Feigenbaum's scenario [11]. Impedance sensors are very well established in the industry due to their versatility and their main appeal for being non-invasive and non-contact. The first attribute is given by the adjustable penetration of the electric field in matter, while the last one is due to the charge induction (capacitive coupling). Impedance sensors can either be individually classified as capacitive and inductive for single frequency applications. In the case of multifrequency systems, impedance sensors measure a spectrum in a wide frequency range. Therefore, impedance sensors can measure the change in either resistance (the real part of the impedance) or reactance (the imaginary part of the impedance) or both. It is known that the resistance depends mostly on both resistivity of the material and electrode (sensor) geometry [14]. Many biological applications use the phase angle given by arctan(reactance/resistance) in order to characterize the sample under study. Therefore, this type of sensor can have great applicability within the context of biomedical engineering, since skin hydration levels are typically characterized by measurements of electrical skin impedance or thermal conductivity, or by optical spectroscopic techniques, including reflectivity. Indirect methods include assessing the mechanical properties of skin or its surface geometry. Among these methods, electrical impedance provides the most reliable and established evaluation, due to its instrumental simplicity and minimized cost [15].

Sensors can also be classified as being passive or active devices. Active sensors require an external power supply to produce a signal at the output, which may be changed according to its properties. Unlike an active sensor, a passive sensor does not need any additional power supply, but it generates an output signal in response to some external stimulus. For example, a thermocouple that generates its own voltage output when exposed to heat. Therefore, passive sensors are direct sensors that change their physical properties, such as resistance, capacitance or inductance [16].

Some applications, in which passive impedance sensors based on chaotic circuits are of great interest, are: i) monitoring of skin hydration and temperature changes [15]; ii) investigations of skin nonlinear properties [17]; iii) investigations related to Bioelectrical Impedance Analysis (BIA) [18]; iv) optimization of bio-oscillators [19][20]. The second application suffers from low sensitivity when measuring its properties. Sensitivity signal may also be related to precision and/or accuracy. Either precision or accuracy of the measured output voltage depends on many things, such as movement artifacts. These artifacts (noise) change significantly the skin impedance which, in turns, cannot not be separated from the total measured impedance. It is known from [17] that skin has a memristive characteristic, where the skin resistance depends on the applied voltage used to characterize it. Therefore, a low output voltage may imply in a low resistance change. Standard impedance sensors may have difficulties to measure those changes. In the case of chaotic sensor, coupled analog or digital filters can be used to analyze the signal as a function of time by using the theory of non-linear dynamic systems in order to remove external noises.

Chaotic resistance sensors are cheap and easy to implement. In addition, it can be implemented to have a high sensitivity to the sample's resistivity change and analyzed by a simpler bifurcation diagram in comparison to the one presented in [1]. Therefore, based on the sensitivity offered by chaotic circuits, this article proposes a active impedance sensor based on the chaotic van der Pol and damped Duffing coupled circuit. This is a typical coupled system of different attractors where the transition from periodic movement to periodic movement is found through chaotic movement in weak coupling. The chaotic region is also shown for the position of periodic window islands, some of which exhibit period doubling phenomena. The latter case, in turn, can be analyzed using a bifurcation diagrams obtained experimentally that will provide a relationship between the resistance, which represents one of the system parameters, and the attractor period [13].

2. Materials and Methods

The dynamics of the system that linearly couples the van der Pol and damped Duffing oscillators is given by:

$$\ddot{x} - \mu(1 - x^2)\dot{x} + x - k(y - x) = 0 \quad (1)$$

$$\ddot{y} + \alpha\dot{y} - y + y^3 - k(x - y) = 0 \quad (2)$$

where μ is a positive parameter that controls one of the model's nonlinear behaviors, α corresponds to the dissipation term and k the coupling constant.

For $k = 0$, both oscillators are decoupled. The Van der Pol exhibits a limit cycle while the Duffing circuit presents a damped oscillatory movement. Certainly, the coupling can be seen as the disturbance which proportionally arises from the difference in their positions.

Lets make $x = x_1$, $y = y_1$, $\dot{x} = x_2$ and $\dot{y} = y_2$, then the system can be rewritten as:

$$\dot{x}_1 = x_2 \quad (3)$$

$$\dot{x}_2 = \mu(1 - x_1^2)x_2 - x_1 + k(y_1 - x_1) \quad (4)$$

$$\dot{y}_1 = y_2 \quad (5)$$

$$\dot{y}_2 = -\alpha y_2 + y_1 - {y_1}^3 + k(x_1 - y_1) \quad (6)$$

This way, an integrating circuit can be built following the schematic shown in figure 1, where τ is the time of integration ($R_b = 100\ k\Omega$ and $C_b = 10\ nF$).

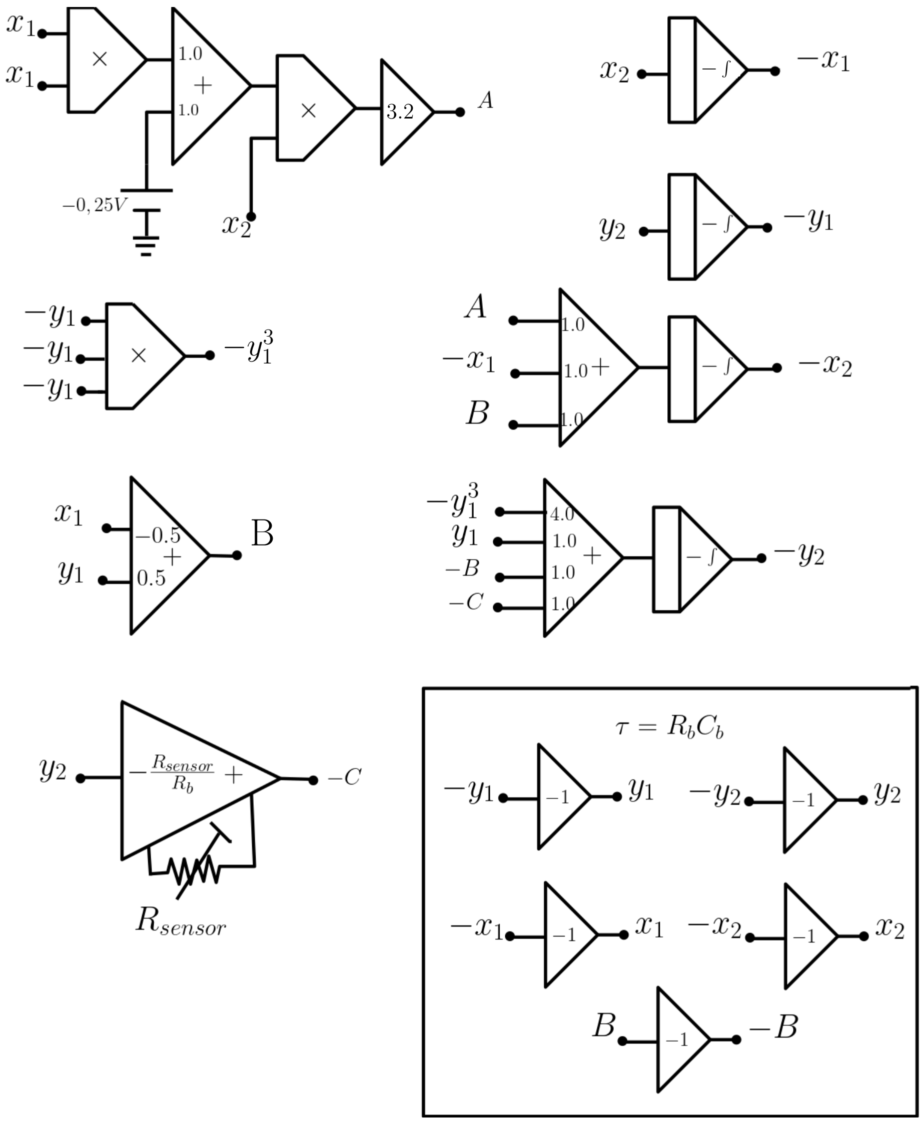

Figure 1. schematic Integrated circuit of the van der Pol and Duffing damped oscillators coupled system.

The circuit was built with the k coupling constant $= 0.5$, $\mu = 0.8$ and $\alpha = \frac{R_{sensor}}{R_b}$. Operational amplifiers were implemented with TL074 and analog multipliers with AD633.

Figure 2 represents the configuration used for the measurements and also the control equipment used for the study of the chaotic circuit. A *National Instruments* data acquisition board was used to read the voltage of variables at a maximum rate of 180 kS/s [1] and also to write parameters with voltage at a maximum rate of 100 kS/s. The connection between this board and the circuit is made by a set of BNC *2090* connectors, which allows the reading of up to eight analog inputs, 2 outputs for parameter control and 20 digital writing or reading ports [13].

[1] S/s=samples per second

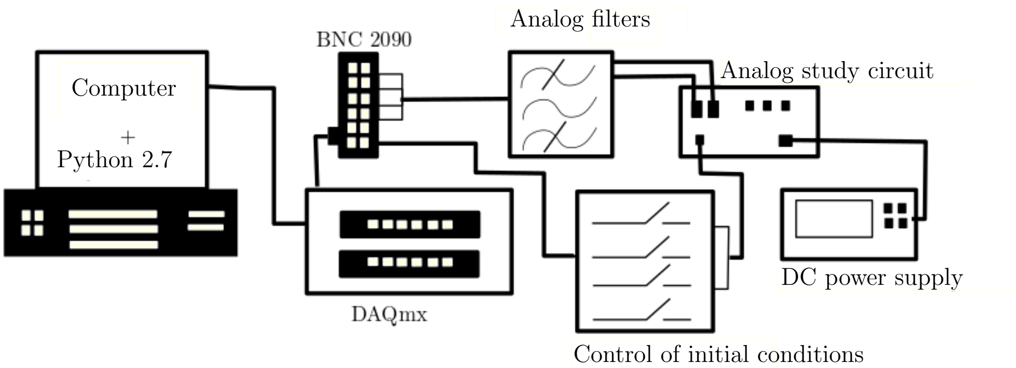

Figure 2. Schematic diagram of the workbench measurement system.

Analog outputs are in the range of $-10V$ and $+10V$ with 16 bits of precision/resolution. The voltages of these two analog channels are controlled by automated routines through the *Python* programming language. Similarly, the analog inputs from the acquisition board contain the same resolution and measurement intervals. All these ports on the acquisition board contain analog filters that measure the variables of the circuit under study. The voltage source ICEL PS-5000 is responsible for supplying the circuit [13]. Figure 3 is a representation of the circuit built for carrying out the tests.

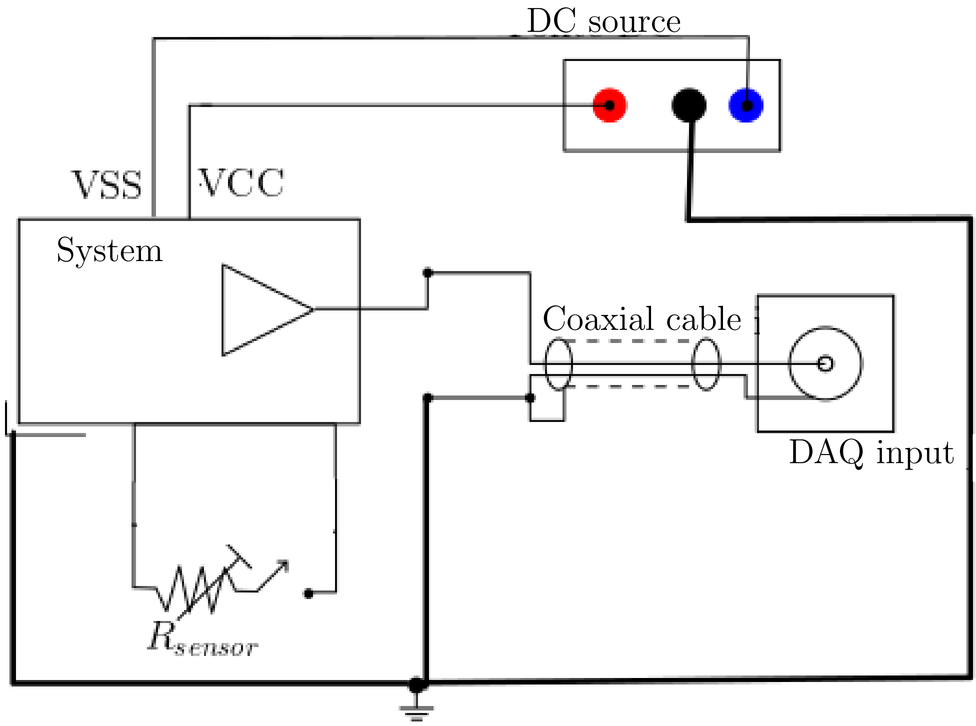

Figure 3. Representation of the bench-mounted circuit for testing.

The voltages do not exceed the region in order to respect the linearity of the integrated circuits (TL074 and AD633). The modulus of the voltage must be less than the $\sqrt[3]{10}$, since the variable ${y_1}^3$ does not exceed 10 V in order to guarantee the AD633's linearity (see figure 3). It is recommended a R_{sensor} ranging from 100 $k\Omega$ to 10 $M\Omega$, resulting in a voltage gain from 0.1 and 1.0 ($=\frac{R_{sensor}}{R_b}$). The relationship between signal and noise should be as high as possible, since the system is chaotic and these must be carefully adjusted and monitored.

A 100 $k\Omega$ potentiometer was used, with a precision of 10 Ω, in order to characterize the α parameter of equation 6. 100 points were collected within the chosen resistance range. These points were collected manually, that is, for each increment in the resistance

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value, a compilation of the Python code was made, which in turn updates the tension value of the variable y_2.

3. Results

An experimental bifurcation diagram was obtained from the coupled van der Pol and Duffing damped oscillators integrated circuit, as shown in Figure 3.

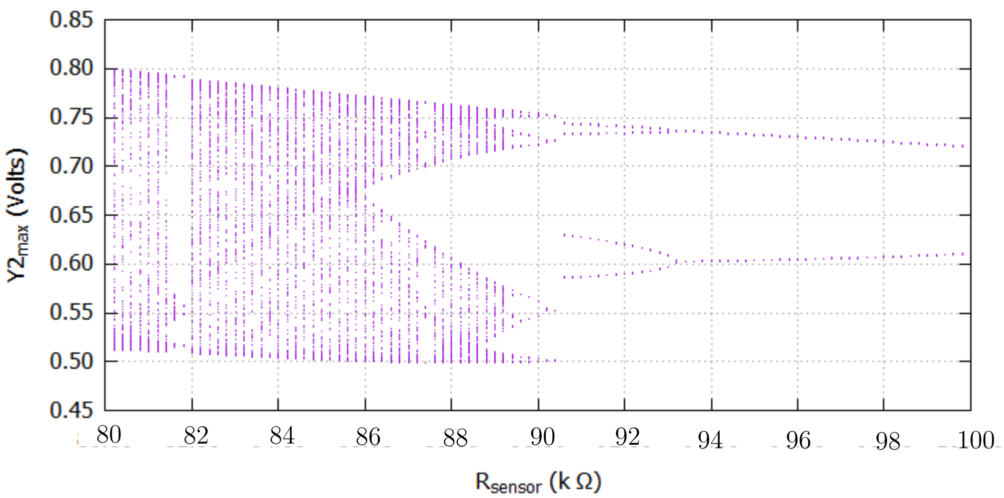

Figure 4. Experimental bifurcation diagram of the coupled van der Pol and cushioned Duffing circuit.

100 points were chosen for data collection. Based on numerical data, [21] chose a resistance range between 80 to 100 $k\Omega$. This region presents the phenomenon called period doubling, which is one of the routes to chaos, this is nothing more than a point in the bifurcation diagram in which the phase space starts to present a period orbit duplicated to the previous one.

Four points were collected, shown in table 1, for the construction of the graph shown in figure 4.

Table 1. Points collected from figure 3 for plotting the graph in Figure 4.

Resistance ($k\Omega$)	Period (s)
91.66	2.0
90.90	4.0
90.20	8.0
89.50	16.0

To obtain the most appropriate curve fit, it is necessary to select in the software a suggestion about the mathematical structure. For this reason, the equation named by normal form was sought, this is obtained when expanding the equations that describe the Taylor series system model around the fixed point. There are several types of bifurcation and for each one of them a specific normal form equation [22]. For the period doubling fork, according to [23], the following equation must be used to adjust the curve:

$$P(R) = a.e^{(-b.R+c)} \tag{7}$$

where P represents the system period, R the sensor resistance and a, b and c are coefficients.

The curve fit for the points in table 1 using equation 7 is shown in Figure 5.

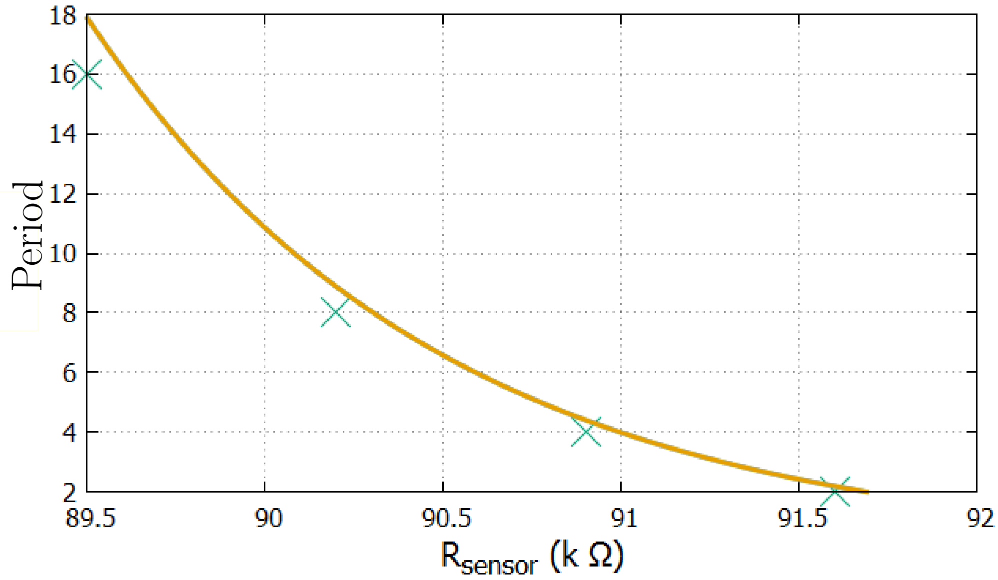

Figure 5. Curve adjustment of equation 7 to the experimental data presented in table 1.

Based on Figure 5, coefficient values of equation (7) are calculated, so that:

$$R(P) = 92.10 - ln\left(\frac{P}{1.237}\right) \tag{8}$$

Based on the sensor's characteristic resistance curve, its sensitivity is calculated. This is defined as the variation of the input parameter required to produce a normalized variation at the output. Generically, sensitivity is defined as a variation of the output signal, for a given variation of the physical input parameter. According to [24], the sensitivity S of a transducer can be calculated as:

$$S = \frac{RFS}{PFS} \tag{9}$$

where RFS is the full-scale resistance and PFS is the measured full-scale period. For the sensor being proposed, according to data in Table 1, it is shown that:

$$S = 150\ \Omega/Period \tag{10}$$

4. Discussion

Even with various ways for implementing chaotic circuits for sensing mentioned in [5] and [1], none of these are focused on impedance sensing for bioimpedance applications. The development of this type of sensor could be applied both to beauty therapy areas, where there is a need to measure the levels of moisture and oiliness [25], as well as to the biomedical field [26], having its importance for investigating thermoregulation, hemodynamic control and metabolite excretion functions. In addition, the presence of elements from the peripheral nervous system in the dermis layer of the skin makes it to be considered an organ for capturing sensory information (heat, cold, pressure, pain and touch) of key importance in researches.

A methodology for measuring impedance is electrical impedance spectroscopy (EIS). Most commercial EIS systems use simple VCVS (voltage controlled voltage source) circuits and then measure the current by a current to voltage converter. Since the load is unknown, part of the driven voltage is lost across the electrode skin interface and then, an erratic current flow is be measured. Most EIS designers prototype its own system for larger bandwidth, lower cost, power excitation control and best portability and usability for users. Those systems work with VCCS (voltage controlled current source) circuits, which have a very high output impedance into comparison to the unknown load. This special characteristic gives a very stable transconductance over a large frequency range. However, the design of a current source should have a chose characteristic to the ideal case. Hence, chaotic sensing circuits might overcome this required specification.

An EIS-based-VCCS system consists in applying a sinusoidal current of multiple frequencies and constant amplitude to the tissue sample, measuring the resulting potential and then calculating the transfer impedance [27]. The sensor proposed in this article has three reasons why it would be more plausible than measuring skin impedance with the current used oscillators. As for the first one, linear current sources, for the most part, operate at the stability margin to achieve high output impedance (an example would be a Howland source). This means that the circuit can easily oscillate, undesirably, if there are disturbances in the component values. The second, symmetrical linear current sources are subject to unbalances, which can cause large voltages as it is common in the load. Lastly, for the third one, the frequency band of current sources has limitations, arising from the restrictions to maintain stability and the operating point.

Another advantage related to biosensors, these have been widely used to measure impedance properties, there are still some technical limitations to be overcome when developing and constructing electrochemical impedance spectroscopy measuring systems. Limitations includes poor sensitivity, difficulties to reuse the electrodes and to detect for small molecules in a sample. However, to proposed sensor is expected to have a high sensitivity due to its chaotic dynamics, be a reusable electrode, be frequency independent and be able to have a self resistance and magnitude adjustment according to the sample under study.

Although resistance values in the order of $k\Omega$ magnitude have been implemented, other values can be investigated. This can be done by exchanging the ampop R_b resistance, which contains R_{sensor}, with a potentiometer, as shown in the figure 6. This can provide a method for measuring the impedance range most used for this type of application. However, you are required to keep the $R_{sensor}/R_{b_{sensor}}$ ratio in the range of 0.1 to 1.0

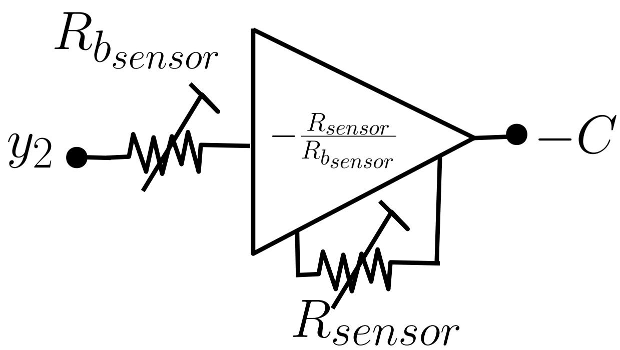

Figure 6. Circuit proposal for adjusting the magnitude of the sample resistance.

Besides, in this research an oscillating sensor was developed to indirectly measure a sample's impedance, whether biological or not, through a known mathematical relationship. The great advantage of this implementation is the absence of an external source of excitation in continuous or alternating current, as is the case in electrical bioimpedance. The circuits of the sensor-oscillator are supplied with a source of continuous voltage, resulting in an alternating voltage with a period that varies with the impedance of the samples in contact with the sensor. It was found that the sensitivity to small variations in the impedance of the sample dramatically changes the dynamic state of the chaotic oscillation system.

Another feature offered by the system is that different regions of the parameter space have characteristic bifurcations of different types, and these bifurcations allow sensor sensitivity to be adjusted according to the application. Given this scenario, it

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is evident the opportunity for future researches that make a comparison between the sensor that has been studied with other techniques of sensing a sample's impedance.

It must be emphasized that it was investigated only one among the various existing phenomena existing in dynamic systems. Other regions of the parameter space could be explored for applicability in sensors, such as the time series synchronization phenomena for both oscillators and the coupling constant, which presented a significant range from 0.3 to 1.0 [13].

Further investigations are required, such as the one related to stochastic resonance phenomena for optimization of sensors [28]. This is due to the fact that the coupling of van der Pol oscillators and damped Duffing would act as a noise signal which is simultaneously feedbacked to the measuring system. Therefore, the hypothesis that the coupling constant can improve the sensor's ability to identify signals through the stochastic resonance phenomenon might be plausible.

Regarding a chaotic sensor for commercial application, care should be taken and more investigation carried out. An alternative is to use a discrete peak detector circuit and a counter for counting the output signal peaks, in this case y_2. This should be carefully studied, since coupling chaotic circuits working with auxiliary circuits may add several difficulties due to noise. However, the visual inspection of folding periods in the bifurcation diagram given by the routines in *Python* might be considered a feasible solution to characterize the impedance change of a sample under study.

Finally, it should be considered that the path of chaos through the period-doubling phenomenon is evident in several chaotic systems by presenting an infinite series of bifurcations with a finite accumulation point. The associated movement beyond that point is chaotic, featuring a route to chaos via Feigenbaum's period or scenario doubling. We believe that the behavior presented by the bifurcation diagram shown in figure 4 is such a case, and visually there is no way to count the period doublings after the 4th step, unless a magnification is done and thus it would be possible to find the steps until chaos is reached. One suggestion is the use of routines, such as TESEAN, to read these longer periods that occur on a smaller scale of parameter variation. TISEAN is a software package (distributed under the GPL license) for analyzing time series with methods based on the theory of nonlinear dynamical systems and it was developed by Rainer Hegger, Holger Kantz and Thomas Schreiber. There are Arduino (open-source electronic prototyping platform) approaches capable of performing automated data processing routines which might be useful for this application. However, the modeling presented here was just an idea among many others found in literature, and, therefore, a potential proposal to support the development of physical sciences and life. This presented model was not related to implement a practical device, but to propose the modeling of an impedance sensor based on a chaotic van der Pol circuit. Although the sensor sensitivity (=150 Ohms/period) may be low for practical applications, bioimpedance solutions are more complex and expensive which, in turns, use signal generators, current sources and voltage meters to measure impedance by means of electrodes placed on skin surface. Therefore, we believe that there are no similar cheap and common sensor/transducer like this one proposed here.

5. Conclusions

The proposal for an impedance sensor based on the coupling of the van der Pol and damped Duffing circuits is advantageous for cases in which it is desired to identify and calibrate small variations in the order of magnitude where disturbances alter the dynamic of chaotic systems.

The application of the results from this research could be used in the development of a low cost commercial device for portable systems with low energy consumption. For this, more practical tests with different types of samples, including biological ones, must be done.

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Author Contributions: Bruna G. Pedro has made the main contributions to the conception of the work and the creation of new analytical models used in the work. David W. C. Marcôndes has contributed to the analysis and interpretation of data. Pedro Bertemes-Filho has drafted the work, substantively revised it and agrees to be personally accountable for the first author's own contributions and for ensuring that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and documented in the literature.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Brown, R.; Chua, L.; Popp, B. Is sensitive dependence on initial conditions nature's sensory device? *International Journal of Bifurcation and Chaos* **1992**, *2*, 193–199.
2. Teodorescu, H.N.L. Sensors based on nonlinear dynamic systems—A survey. 2017 International Conference on Applied Electronics (AE). IEEE, 2017, pp. 1–10.
3. Karimov, T.; Nepomuceno, E.G.; Druzhina, O.; Karimov, A.; Butusov, D. Chaotic Oscillators as Inductive Sensors: Theory and Practice. *Sensors* **2019**, *19*, 4314.
4. Teodorescu, H.N.L.; Cojocaru, V.P. Biomimetic chaotic sensors for water salinity measurements and conductive titrimetry. 2012 Third International Conference on Emerging Security Technologies. IEEE, 2012, pp. 182–185.
5. Gammaitoni, L.; Bulsara, A. Noise Activated Nonlinear Dynamic Sensors. *Physical review letters* **2002**, *88*, 230601. doi:10.1103/PhysRevLett.88.230601.
6. Gammaitoni, L.; Bulsara, A. Nonlinear sensors activated by noise. *Physica A: Statistical Mechanics and its Applications* **2003**, *325*, 152–164.
7. Korneta, W.; Gomes, I. Noise activated bistable sensor based on chaotic system with output defined by temporal coding and firing rate. *Chaos: An Interdisciplinary Journal of Nonlinear Science* **2017**, *27*, 111103. doi:10.1063/1.5006564.
8. Wang, G.; Chen, D.; Lin, J.; Chen, X. The application of chaotic oscillators to weak signal detection. *IEEE Transactions on industrial electronics* **1999**, *46*, 440–444.
9. Ling, Y.f.; Chen, C.x.; Niu, D.z.; Chen, T. Weak Signal Detection Using Double-Well Duffing–van der Pol Oscillator and Formulation of Detection Statistics. *Journal of the Physical Society of Japan* **2019**, *88*, 044001.
10. Korneta, W.; Iacyel, G.; Rodrigo, P.; Zabovsky, M. Nonlinear sensor driven by chaotic dynamics. ANNA'18; Advances in Neural Networks and Applications 2018. VDE, 2018, pp. 1–4.
11. Hoff, A. Estruturas de Bifurcação em Sistemas Dinâmicos Quadridimencionais. *Dissertação de Mestrado Acadêmico em Física* **2014**.
12. Marcondes, D.C. Controle de Parâmetros via Tensão Contínua: uma Aplicação em Dinâmica Não-Linear. Master's thesis, Univ. Universidade do Estadoo de Santa Catarina, 2017.
13. Pedro, B.G. Acoplamento Dos Osciladores Van Der Pol e Duffing Amortecido: Uma abordagem Experimental. *Dissertação de Mestrado Acadêmico em Física* **2019**.
14. Carminati, M. Advances in high-resolution microscale impedance sensors. *Journal of Sensors* **2017**, *2017*.
15. Huang, X.; Yeo, W.H.; Liu, Y.; Rogers, J.A. Epidermal differential impedance sensor for conformal skin hydration monitoring. *Biointerphases* **2012**, *7*, 52.
16. Sinclair, I. *Sensors and transducers*; Elsevier, 2000.
17. Pabst, O. Rectifying memristor bridge circuit realized with human skin. *Journal of Electrical Bioimpedance* **2018**, *9*, 184–192. doi:10.2478/joeb-2018-0023.
18. Bertemes-Filho, P.; Valicheski, R.; Pereira, R.; Paterno, A. Bioelectrical impedance analysis for bovine milk: Preliminary results. Journal of Physics: Conference Series. IOP Publishing, 2010, Vol. 224, p. 012133.
19. Shitiri, E.; Vasilakos, A.V.; Cho, H.S. Biological oscillators in nanonetworks—Opportunities and challenges. *Sensors* **2018**, *18*, 1544.
20. Huertas, G.; Maldonado, A.; Yúfera, A.; Rueda, A.; Huertas, J.L. The Bio-Oscillator: A Circuit for Cell-Culture Assays. *IEEE Transactions on Circuits and Systems II: Express Briefs* **2015**, *62*, 164–168.
21. Woafo, P.; Chedjou, J.; Fotsin, H. Dynamics of a system consisting of a van der Pol oscillator coupled to a Duffing oscillator. *Physical Review E* **1996**, *54*, 5929.
22. Onias, H.H.S. Bifurcações Dinâmicas em Circuitos Eletrônicos. *Dissertação de Mestrado em Física* **2012**.
23. P duplicação do período. *9*, 3958. doi:10.4249 / scholarpedia.3958.
24. Limited, G.I. Calculating Sensitivity and Full Scale Output. *Helpsheet, 125*.

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25. *Analisador De Pele Digital Bio impedância Oleosidade Umidade, howpublished = https://www.fabricadomicropigmentador.com.br/produtos/analisador-de-pele-digital-bio-impedancia-oleosidade-umidade/, note = Accessed: 2010-09-11*.
26. Ferreira, D.M. Impedância Elétrica na Determinação de alterações da Pele Provocadas por Substâncias Irritantes. PhD thesis, UFRJ, 2006.
27. Bertemes-Filho, P.; Negri, L.; Felipe, A.; Vincence, V. Mirrored modified Howland circuit for bioimpedance applications: Analytical analysis. Journal of Physics: Conference Series. IOP Publishing, 2012, Vol. 407, p. 012030.
28. Barreto, M.A. Aplicação de Ressonância Estocástica em Medidas Eletrofisiológicas **2015**.