Eur. Phys. J. Special Topics **225**, 127–136 (2016)

DOI: 10.1140/epjst/e2016-02625-8

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

A novel memristive time–delay chaotic system without equilibrium points

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Received 14 June 2015 / Received in final form 14 January 2016
Published online 29 February 2016

Abstract. Memristor and time–delay are potential candidates for constructing new systems with complex dynamics and special features. A novel time–delay system with a presence of memristive device is proposed in this work. It is worth noting that this memristive time–delay system can generate chaotic attractors although it possesses no equilibrium points. In addition, a circuitry implementation of such time–delay system has been introduced to show its feasibility.

1 Introduction

There has been increasing attention to chaotic systems because of their broad range applications, such as in secure communications, cryptography, biology, robotics or modelling multi–disciplinary phenomena [1–4]. Various chaotic systems were introduced over the last decades [5–9]. Recently, chaotic systems with hidden attractors from a computational point of view [10–12] have been investigated. These chaotic systems include for example the systems with only one stable equilibrium [13–15], with a line containing infinitely many equilibrium points [16], and especially with no equilibria [17,18]. We face a challenge of discovering hidden attractor because there is no systematic way to find initial conditions that lead to these attractors except by extensive numerical search [19–21]. Hidden attractors are important in engineering applications due to their appearance that allow unexpected and disastrous responses [12,16,22].

The limit of the calculation speed, memory effects, finite transmission velocity etc. lead unavoidable presences of time delays in various fields such as engineering [23,24],

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neural system [25], physics [26] or biology [27,28]. In addtion, different practical models, for example a single vehicle induced by traffic light and speedup [29], broadband bandpass electro–optic oscillator [30], road traffic [31], or food web systems [32], etc. can be described more accurately by using time–delay systems. Especially, the systems described by first order delay differential equations (DDE) can exhibit chaos [33–39]. Infinite dimensional dynamics and simple structure of such time–delay chaotic systems have studied and applied [40–47]. It is noting that the reported time–delay chaotic systems have a limit number of equilibrium points. It is very interesting to ask naturally whether there exists a time–delay system with uncountable number of equilibrium points or without equilibrium points.

The realization of solid–state thin film two–terminal memristor at Hewlett-Packard Labs [48] opens new research areas of memristor–based applications like high–speed low–power processors [49], adaptive filter [50], pattern recognition systems [51], associative memory [52], neural networks [53,54], programmable analog integrated circuits [55], and so on [56,57]. In addition, recent researches show that the intrinsic nonlinear characteristic of memristor has been exploited in constructing chaotic systems with many interesting features [58–61]. For instance, memristor–based chaotic systems with uncountable infinite number of equilibria were presented in [60,62,63]. A simple memristive chaotic system including only three elements (an inductor, a capacitors and a memristor) was introduced in [64]. Hyperchaos was generated by combining a memristor with cubic nonlinear characteristics and a modified canonical Chua's circuit [65].

Motivated by the above researches, the combination of memristor and time–delay for designing new chaotic systems with special features should be considered. A novel memristive time–delay chaotic system without equilibrium points is proposed in this work. The rest of the paper is organized as follows. In Sect. 2, the model of the memristive device is introduced briefly. The new memristive time–delay system and its fundamental dynamics are investigated in Sect. 3. Circuital implementation of the proposed time–delay system is presented in Sect. 4. Finally, the conclusions are drawn in Sect. 5.

2 Model of the memristive device

After the invention of L.O. Chua [66], memristor is known as the fourth basic circuit element beside the three conventional ones (the resistor, the capacitor, and the inductor). Memristor represents the relationship between two fundamental circuit variables, the charge and the flux [57,66]. There are two kinds of memristor: charge-controlled memristor and flux–controlled memristor [57,60]. Moreover, memristive systems have been introduced by generalizing the original definition of a memristor [67]. A memristive system is given as

$$\begin{cases} \dot{x} = F(x,u,t) \\ y = G(x,u,t)u, \end{cases} \tag{1}$$

where u, y, and x denote the input, output and state of the memritive system, respectively. The function F is a continuous n–dimension vector function and G is a continuous scalar function [67].

In this work, we use a memristive device which is described by

$$\begin{cases} \dot{x}_2 = dx_1 \\ h(x_1,x_2) = (0.1x_2 - 1)x_1, \end{cases} \tag{2}$$

where x_1 and x_2 are the input and internal state of the memristor device. Here $h(x_1, x_2)$ presents the output of the memristor device while d is a positive parameter.

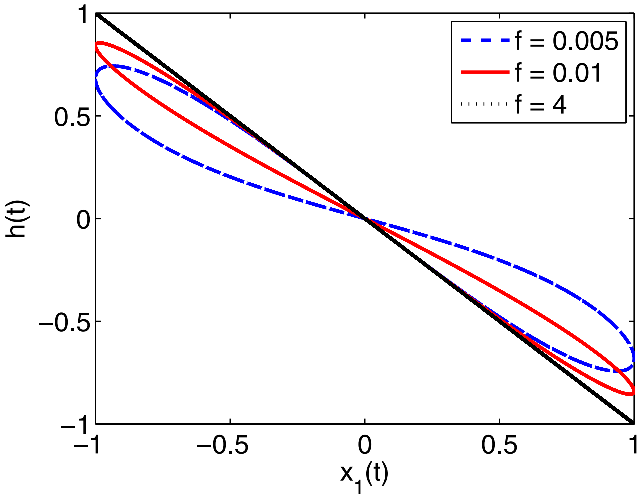

Fig. 1. Hysteresis loops of the proposed memristive device (2) driven by a sinusoidal stimulus (3) when $X_1 = 1$, $x_2(0) = 0$ and varying frequency f.

In this section, the value of parameter d is 0.1. The memristive device (2) is quite similar to the known one [68].

In order to explore the fingerprints of memristive device (2), we apply an external bipolar period signal across its terminals [69]. The applied sinusoidal stimulus has the following form

$$x_1(t) = X_1 \sin(2\pi f t), \tag{3}$$

in which X_1 is the amplitude, and the f is the frequency. From the first equation of (2), the internal state variable of the memristive device is given by

$$\begin{aligned} x_2(t) &= \int_{-\infty}^{t} dx_1(\tau)d\tau = dx_1(0) + d\int_0^t X_1 \sin(2\pi f\tau)\, d\tau \\ &= dx_1(0) + \frac{dX_1}{2\pi f}(1 - \cos(2\pi f t)), \end{aligned} \tag{4}$$

where $x_2(0) = \int_{-\infty}^{0} x_1(\tau)d\tau$ is the initial condition of the state variable x_2. Substituting (3) and (4) into (2), the output of the memristive device is

$$h(t) = \left(0.1dx_1(0) + \frac{0.1dX_1}{2\pi f} - 1\right) X_1 \sin(2\pi f t) - \frac{0.1dX_1^2}{4\pi f}\sin(4\pi f t). \tag{5}$$

Obviously, the output of the memristive device depends on the frequency and amplitude of the input stimulus. Moreover, the output h also depends on the initial state of the memristive device. Figures 1–3 show three main fingerprints of the memristive device (2).

3 New memristive time–delay system

Based on memristive device (2), a novel time–delay system is proposed as follows

$$\begin{cases} \dot{x}_1 = -ax_{1\tau} + \operatorname{sgn}(x_{1\tau}) - bh(x_1, x_2) - c \\ \dot{x}_2 = dx_1, \end{cases} \tag{6}$$

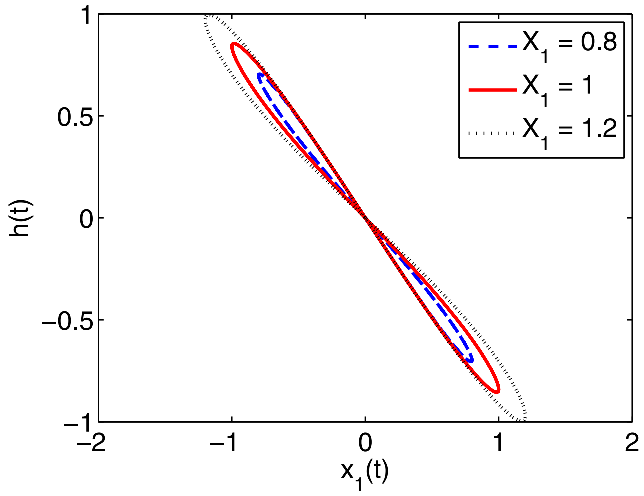

Fig. 2. Hysteresis loops of the proposed memristive device (2) driven by a sinusoidal stimulus (3) when $f = 1$, $x_2(0) = 0$ and changing input amplitude X_1.

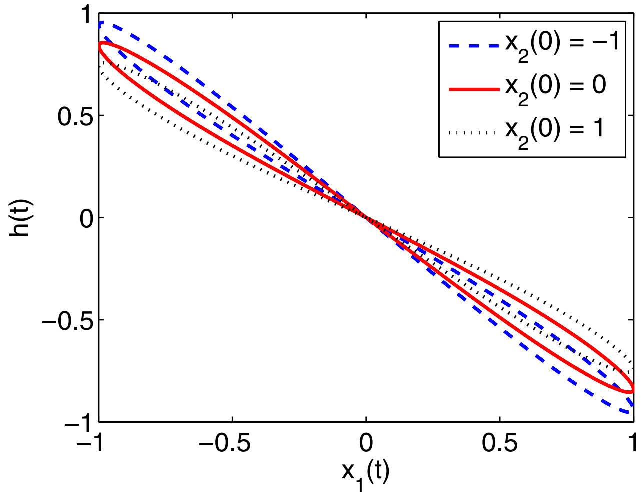

Fig. 3. Hysteresis loops of the proposed memristive device (2) driven by a sinusoidal stimulus (3) when $X_1 = 1$, $f = 0$ and using different initial states $x_2(0)$.

where a, b, c, d are positive real parameters ($d \neq 0$), τ is the time–delay, x_τ denotes $x\,(t-\tau)$, and $h(x_1, x_2)$ is the output of the memristive device as presented in (2).

It is easy to derive the equilibrium points of the memristive time–delay system (6) by solving $\dot{x}_1 = 0$ and $\dot{x}_2 = 0$, that is

$$-ax_1 + \mathrm{sgn}\,(x_1) - b\,(0.1x_2 - 1)\,x_1 - c = 0 \tag{7}$$

$$dx_1 = 0. \tag{8}$$

When $c = 0$, the memristive time–delay system (6) has infinite equilibrium points $E\,(0, x_2)$. It is interesting that, the time–delay system (6) is chaotic for different values of the parameters (a, b, d, and τ). For example, when choosing $a = 1.8$, $b = 0.02$, $d = 0.1$, $\tau = 1$ and the initial conditions $(x_1(0), x_2(0)) = (0.1, 0.1)$, chaotic behavior

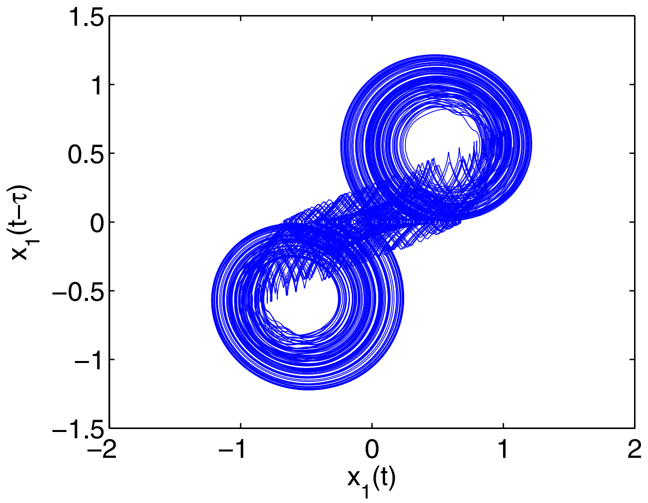

Fig. 4. Chaotic attractor with no equilibria of the novel memristive time–delay system (6) when $a = 1.8$, $b = 0.02$, $c = 0.001$, $d = 0.1$, $\tau = 1$ and the initial conditions $(x_1(0), x_2(0)) = (0.1, 0.1)$.

can be observed. In this case, the maximum Lyapunov exponent $\lambda_{\max}$ calculated using the algorithm in [70,71] is positive ($\lambda_{\max} = 0.3132$). There is rarely a reported time–delay system with an infinite number of equilibrium points [71].

Interestingly, when $c \neq 0$, as can be seen from Eq. (8), this leads to $x_1 = 0$ which is inconsistent with Eq. (7). As a result, the proposed memristive time–delay system has no equilibrium points. Moreover, when $a = 1.8$, $b = 0.02$, $c = 0.001$, $d = 0.1$, $\tau = 1$ and the initial conditions $(x_1(0), x_2(0)) = (0.1, 0.1)$, the memristive time–delay system (6) depicts a strange chaotic attractor without equilibrium as shown in Fig. 4. In this case, the corresponding maximum Lyapunov exponent is $\lambda_{\max} = 0.2837$. Although there are existing literature on memristive time delay systems as well as delayed networks with memristive neurons [72–78], the absence of equilibria makes such new time–delay system significantly different from reported systems. We will concentrated on this case. The bifurcation diagram with respect to the parameter a is presented in Fig. 5 by plotting the local maxima of the state variable $x_1(t)$ when varying the value of the parameter a. In addition, the maximum Lyapunov exponent for the memristive time–delay system is shown in Fig. 6. The results show that the system can exbibit chaotic behavior for $a > 1.61$.

4 Circuital implementation of the memristive time–delay system

An important feature relating to chaotic systems and their applications is their feasibilities [1,79,80]. For example, circuital realization of theoretical chaotic model plays a vital role in practical chaos–based applications such as secure communications, random numbers generator, image encryption process, or path planning for autonomous robots [81–84]. Therefore, in this section, a circuital realization of the memristive time–delay system without equilibrium (6) is presented briefly to illustrate the feasibility and correctness of the theoretical model.

The designed circuit is shown in Fig. 7 in which the variable x_1 of time–delay system (6) is the voltages across the capacitor C_1. It easy to see the presence of memristive device and time–delay unit. By applying Kirchhoff's circuit laws, the

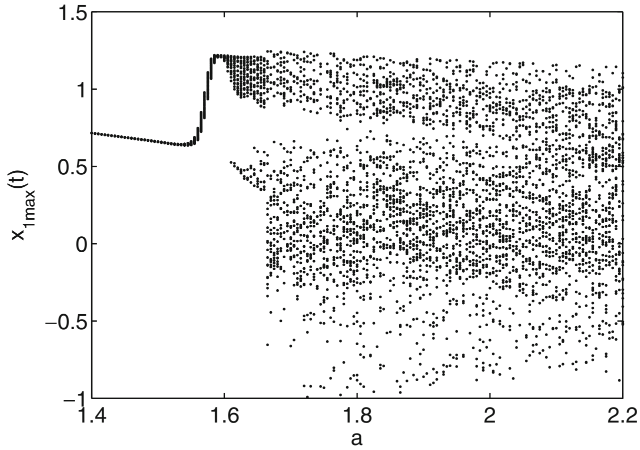

Fig. 5. Numerical bifurcation diagram for the novel memristive time–delay system (6) when $b = 0.02$, $c = 0.001$, $d = 0.1$, $\tau = 1$, the initial conditions $(x_1(0), x_2(0)) = (0.1, 0.1)$, and a as a varying parameter.

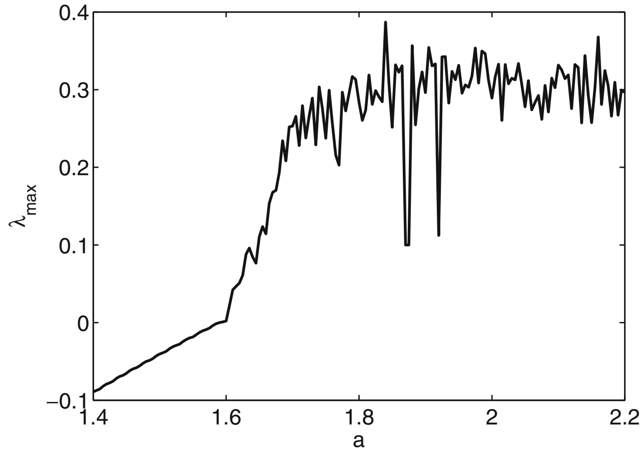

Fig. 6. Maximum Lyapunov exponents for the novel memristive time–delay system (6) versus the parameter a when $b = 0.02$, $c = 0.001$, $d = 0.1$, $\tau = 1$, and the initial conditions $(x_1(0), x_2(0)) = (0.1, 0.1)$.

equation of the circuit in Fig. 7 is derived as:

$$\frac{dx_1}{dt} = -\frac{1}{R_1C_1}x_{1\tau} + \frac{V_{sat}}{R_2C_1}\text{sgn}\,(x_{1\tau}) - \frac{1}{R_3C_1}h(x_1, x_2) - \frac{1}{R_4C_1}V_c, \tag{9}$$

where V_{sat} is the saturation voltage of the operational amplifier U_2.

In this work, the power supplies are ± 15 volts and the values of components are chosen as follows: $R_1 = 0.555k\Omega$, $R_2 = 14.25k\Omega$, $R_3 = 50k\Omega$, $R_4 = 1M\Omega$, $C_1 = 1\mu F$, and $V_c = 1V_{DC}$.

Another main component of the circuit in Fig. 7 is the memristive device, of which output is $h(x_1, x_2)$. The memristive device is also emulated by electronic components such as resistors, a capacitor and an analog multiplier (see Fig. 8). The input, output and the internal state of the memristive device are x_1, $h(x_1, x_2)$, and x_2, respectively. Here the internal state of the memristive device x_2 is the voltage across the

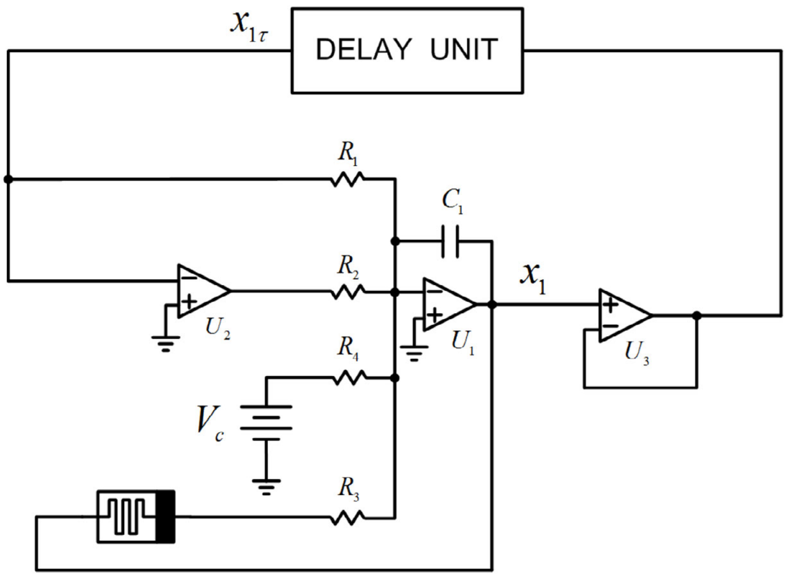

Fig. 7. Circuital schematic of the new time–delay chaotic system without equilibrium (6) based on the memristive device (2).

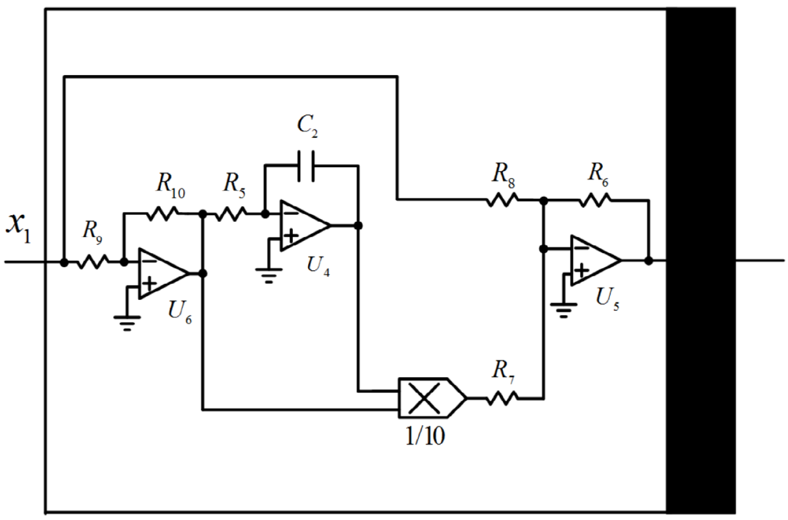

Fig. 8. Circuital implementation which emulates the memristor device. The values of components are selected as: $R_5 = R_6 = R_7 = R_8 = R_9 = R_{10} = 10k\Omega$, and $C_2 = 1\mu F$.

capacitor C_2. Therefore, the memristive device is described by the following circuital equations

$$\begin{cases} \dfrac{dx_2}{dt} = \dfrac{1}{R_5 C_2} x_1 \\ h(x_1, x_2) = \left(\dfrac{R_6}{10R_7} x_2 - \dfrac{R_6}{R_8} \right) x_1. \end{cases} \tag{10}$$

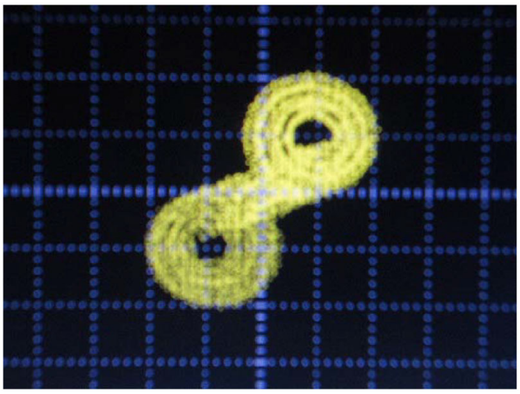

Fig. 9. Experimental chaotic attractor of the designed electronic circuit obtained by using an oscilloscope in the $x_1(t) - x_1(t - \tau)$ plane.

The delay unit is implemented by a series of Bessel filters in cascade [85]. The value of the delay in the delay unit is $T_{delay} = 1\,\text{ms}$. The dimensionless delay τ is calculated by

$$\tau = \frac{T_{delay}}{R^* C^*}, \tag{11}$$

with $R^* = 1k\Omega$ and $C^* = 1\mu F$, so that $\tau = 1$.

The designed circuit has been implemented on breadboards with discrete off–the–shelf components. Experimental observation of phase space by an oscilloscope in the laboratory is presented in Fig. 9. A good agreement between the theoretical attractor (Fig. 4) and the experimental one (Fig. 9) shows the feasibility of the novel memristive time–delay system without equilibrium points.

5 Conclusion

A novel time–delay chaotic system with the presence of a memristive device has been proposed in this work. It is worth noting that such memristive time–delay system possesses no equilibrium points. We have investigated the possibility of designing new systems exhibiting chaotic behavior by combining memristive device and time delay. Moreover, the discovery of this new memristive time–delay system contributes towards knowledge about the relation between the local features of equilibrium points and the global complex behaviors of a dynamical system.

Time–delay systems have several applications in secure communications due to their complex dynamics which are governed by the presence of delays [43,45,86–88]. Therefore, such memristive time–delay system has potential applications in chaos–based communications because of its chaos and feasibility. Further studies in this research direction will be presented in future works.

The authors would like to thank the Editor and the Reviewers for their valuable comments and suggestions. The authors are grateful to Prof. Lidan Wang and Prof. Shukai Duan, School of Electronic and Information Engineering, Southwest University, for their useful suggestions. This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.02–2012.27. The fifth author acknowledges also support from Russian Scientific Foundation (14–21–00041) and Saint Petersburg State University.

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