Improved One-Dimensional Piecewise Chaotic Maps for Information Security

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Abstract—Chaos represents interesting features that are suitable for the cryptography domain. One-dimensional chaotic maps are widely used for security issues due to their simplicity and chaotic behavior versus other multidimensional chaotic maps that can be complex for hardware implementation and hard to analyze. However, classical one-dimensional chaotic maps present a reduced range of chaotic behavior. In this paper, we propose two new piecewise compound one-dimensional chaotic maps; an Altered Sine-Logistic map based on Tent map (ASLT) and a combined Cubic-Tent map (CT). The proposed compound maps combine classical and simple one-dimensional chaotic maps to produce an extensive range of chaotic behavior. The ASLT system comprises a combined Sine-Tent map in the first piece of the function and a combined Logistic-Tent map in the second piece of the function. Then, the CT map is based on the nonlinear fusion operation between the Cubic map and the piecewise Tent map. Simulation results and chaotic behavior analysis are provided using the bifurcation diagram, Lyapunov exponent, initial sensitivity, and Shannon entropy measure. The evaluation results demonstrate the effectiveness of the proposed 1D maps with better chaotic performances, chaotic range, and complexity compared to their corresponding classical chaotic maps. The simple structure and effectiveness of the proposed systems make them suitable for chaos-based cryptography providing better security strength and more randomness.

Index Terms—Chaotic map, chaotic range, Lyapunov exponent, bifurcation diagram, Initial sensitivity

I. Introduction

Nowadays, information security represents an important requirement with the advancement in communication and technology. In particular, the security of the transmitted images, which include personal information. Various image encryption schemes have been introduced in order to ensure real-time secure image transmission.

In the past two decades, there has been a significant interest in the chaotic system and its use for image cryptography [1]–[5] among various encryption methods due to its interesting properties, such as initial sensitivity, pseudo-randomness, and unpredictability. In particular, standard 1D chaotic systems are widely used because of their simplicity and dynamic behavior. However, they are not secure and cannot resist many well-known attacks such as chosen-plaintext attack, known-plaintext attack, brute force attack because of their limited and interrupted chaotic range, low chaotic complexity, and higher dynamic behavior degradation rate [4]. Therefore, researchers aim to improve the chaotic properties of the 1D chaotic map by combining standard ones to provide better security strength and more randomness [4], [6]–[9].

Zhu *et al*. proposed a new compound chaotic system based on Sine and Tent chaotic maps (STS) to extend the chaotic range and increase the chaotic performance of 1D discrete chaotic maps [10]. The new 1D map is used to generate S-boxes then double S-boxes are used for image encryption purposes making the cryptosystem more secure and reducing the time cost. Wang et al. introduced a new and improved 1D sinusoidal chaotic map (I1DS) for image encryption. The proposed map combines standard and simple one-dimensional chaotic maps (Logistic and Sine) [6]. The chaotic behavior of the new chaotic map is improved, but it is still not chaotic at some points in the range [0,1]. Zhu et al. proposed a new combination of Logistic and Tent chaotic maps to produce chaotic sequences [11]. Then the combined map with a proposed fitness function is used to generate an efficient S-box, which will be used for image encryption.

Farah *et al*. proposed a new hybrid chaotic map that exhibits an excellent randomness performance and sensitivity. The new chaotic map is composed of the Logistic map, Tent map, and Sine map [12]. It presents high values of Lyapunov exponents and Shannon entropy. Li *et al*. proposed Compressive Sensing (CS) based image compression, authentication, and encryption in the cloud [1]. For that, a new Logistic-Tent-Sine chaotic map (LTSS) is proposed; the proposed map has a more extensive chaotic range and better chaotic behavior than standard 1D chaotic maps. The LTSS is used to construct a Binary Data Cyclic Encryption algorithm (BDCE) chaotic stream cipher for encrypting the low-frequency part of images.

This paper proposes new combined one-dimensional chaotic maps based on the standard 1D chaotic maps. The first map is based on altering the Sine and the Logistic map into the piecewise Tent map (ASLT). Furthermore, the second 1D proposed chaotic map is the Cubic-Tent map (CT), it is based on the Cubic and the Tent maps. The

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compound maps have an improved extensive chaotic range and better chaotic performance and efficiency than the standard one-dimensional systems. To demonstrate the effectiveness of proposed systems, they are evaluated in terms of the bifurcation diagram, Lyapunov exponent, initial state sensitivity, and Shannon entropy. The simulation results and chaotic behavior analysis prove the extensive chaotic range of the ASLT without any interruption and the CT map with some interruptions. In addition, the results prove the high sensitivity of the proposed combined chaotic maps, thus a good randomness property suitable for a good level of security for an efficient cryptosystem. The paper is organized as follows. Section 2 introduces the standard maps and the new proposed 1D maps. Section 3 presents the simulation results, the performance analysis, and the comparison of the new proposed chaotic maps with their corresponding standard maps. Finally, some concluding remarks and perspectives are given in Section 4.

II. The Proposed 1D Combined Chaotic Systems

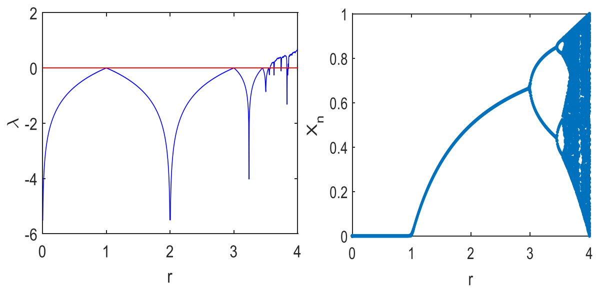
Different chaotic functions are proposed to build the chaotic maps, which can be complex for hardware implementation and challenging to analyze. For these reasons, simpler one-dimensional chaotic maps are chosen for image encryption instead of complicated and multidimensional chaotic maps. This section first reviews four standard 1D chaotic maps: The Logistic, Sine, Tent, and Cubic maps. Second, these maps will be used for constructing two new 1D chaotic systems.

A. Standard One Dimensional Chaotic Maps

1) Logistic Map: The Logistic map is one of the simplest chaotic maps, which has been frequently exploited by research for many applications like image encryption [11]-[13]. It is a polynomial mapping of degree 2, introduced by Robert in 1976 [14]. One dimensional Logistic map generates 1-D sequences in [0, 1], it is described as follows:

$$x_{n+1} = r x_n (1 - x_n) \tag{1}$$

where n is the map iteration index, $0 \le r \le 4$ is the control parameter and x_0 is the initial condition. From the bifurcation diagram Fig. 1.b we notice some periodic (non-chaotic) discontinuous chaotic windows before $r = 3.99$.



(a) (b)

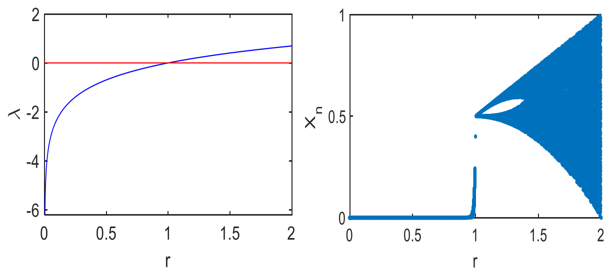
Fig. 1. Lyapunov graph (a) and bifurcation diagram (b) of the Logistic map.

To address this problem, values corresponding to positive Lyapunov exponents should be selected for parameter r to keep the effectiveness of the cryptosystem. Therefore, the values of r should be $\in [3.5699456,4]$, this interval represents the chaotic region of the Logistic map as shown in Fig. 1.a, but some points in this region still did not present a chaotic behavior. Then, the Logistic map has a limited chaotic and interrupted chaotic range that can be beneficial for brute-force attacks.

2) Tent Map: The Tent map is a piecewise function that generates chaotic sequences in [0 1]. Mathematically, its generalized form can be defined as [15]:

$$x_{n+1} = \begin{cases} r x_n, & if\ x_n < 1/2 \\ r(1 - x_n), & if\ x_n \ge 1/2 \end{cases} \tag{2}$$

Here the range of r is [0,2], but the Tent map exhibits chaotic behavior for every value of the control parameter $r \in [1,2]$ as shown in Fig. 2, which chaotic range is better than that of the Logistic map.



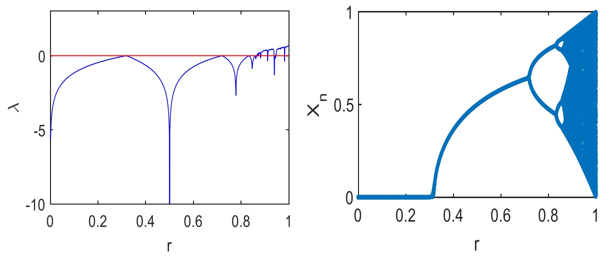
(a) (b)

Fig. 2. Lyapunov graph (a) and bifurcation diagram (b) of the Tent map

3) Sine Map: The Sine map is another commonly used one-dimensional chaotic map; it is based on the sine function that maps the input angle within the interval [0, 1] into the same interval [16]. Mathematically, the Sine map is described by

$$x_{n+1} = r \sin(\pi x_n), \tag{3}$$

where the control parameter $r \in [0,1]$. To observe the chaotic behaviors of the Sine map, its Lyapunov exponent and bifurcation diagram are presented in Fig. 3.a and Fig. 3.b, respectively. The Sine map is chaotic when r is $\in [0.867,1]$, thus chaotic range is limited and interrupted, having the same behavior as the Logistic map.



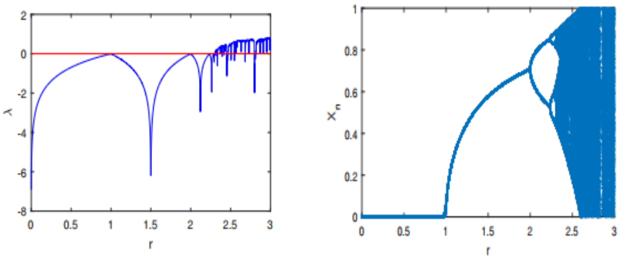
(a) (b)

Fig. 3. Lyapunov graph (a) and bifurcation diagram (b) of the Sine map.

4) Cubic Map: The Cubic map is another commonly used map to generate chaotic sequences. It produces chaotic sequences in [0,1]. It is defined by [17]:

$$x_{n+1} = r x_n (1 - x_n^2), \tag{4}$$

r represents the control parameter of the map, it is ranged in [0,3]. The Cubic map is chaotic when r is $\in [2.59,3]$, therefore, the chaotic range is also limited and presents many interruptions, as shown in Fig. 4.



(a) (b)

Fig. 4. Lyapunov graph (a) and bifurcation diagram (b) of the Cubic map.

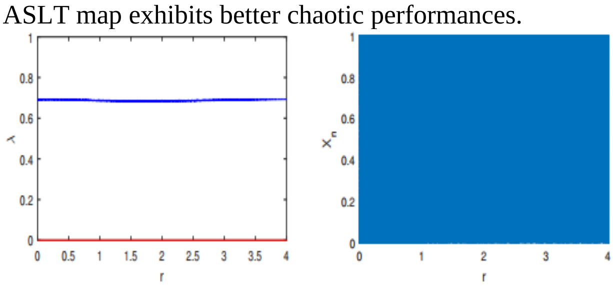
B. *New Proposed Combined 1D Chaotic Maps*

Motivated by compound one-dimensional chaotic maps, this section proposes two new 1D piecewise maps based on combinations of existing 1-D chaotic maps.

1) Altered Sine-Logistic based Tent map: In our paper, we propose a new combined one-dimensional chaotic map based on piecewise Tent map by altering the Sine map and the Logistic map. The ASLT is defined as follows:

$$x_{n+1} = \begin{cases} \frac{4-r}{4}\sin(\pi x_n) + \frac{r}{2}x_n & if\ \ x_n < 0.5 \\ (4-r)x_n(1-x_n) + \frac{r}{2}(1-x_n) & if\ \ x_n \geq 0.5 \end{cases} \quad (5)$$

where r is the control parameter in the range [0,4], the combined map exhibits a chaotic behavior when $r \in [0,4]$ as shown in Fig. 5, meaning that the proposed map is always chaotic in the definition domain. Fig. 5.a and Fig. 5.b represent the Lyapunov exponent and the bifurcation diagram of the ASLT system, respectively. We can see that the chaotic range of the ASLT map is much larger than their corresponding chaotic maps (Logistic, Sine, and Tent maps). The proposed map outputs uniformly distributed sequences within [0, 1] (see Fig. 5.b). Hence, the proposed ASLT map exhibits better chaotic performances.



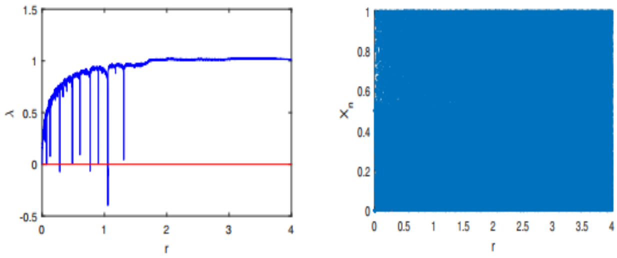
(a) (b)

Fig. 5. Lyapunov graph (a) and bifurcation diagram (b) of the New proposed ASLT map.

2) Cubic-Tent map: The second proposed 1D chaotic map is the piecewise Cubic-Tent (CT) map. It is composed of the Cubic map and the Tent map as follows:

$$x_{n+1} = \begin{cases} mod\left(\left(4-\frac{3}{4}r\right)x_n(1-x_n^2) + \frac{r}{2}x_n, 1\right) & if\ x_n < 0.5 \\ mod\left(\left(4-\frac{3}{4}r\right)x_n(1-x^2) + \frac{r}{2}(1-x_n), 1\right) & if\ x_n \geq 0.5 \end{cases} \quad (6)$$

where r is the control parameter, n is the iteration number, and the mod is the modulo operation. The modulo operation is to ensure output data within the range of [0,1]. Fig. 6 presents the Lyapunov exponent and the bifurcation diagram of the CT map, respectively; it shows a chaotic behavior in the entire interval [0,4] , with some interruptions.



(a) (b)

Fig. 6. Lyapunov graph (a) and bifurcation diagram (b) of the New proposed Cubic-Tent map.

III. Results and Discussions

This section presents the experimental setup and results of the presented paper. Initially, chaotic maps were implemented using MATLAB R2018b on a 64-bit machine having a Corei5 processor and 8 GB RAM. The chaotic performance and dynamic properties of the proposed maps compared to their corresponding 1D maps are studied in this section. The comparison is performed using the bifurcation diagram, Lyapunov Exponent (LE), initial sensitivity, and Shannon Entropy (SE). We use the same range, $r \in [0,4]$, in all experiments. The analysis and comparison results demonstrate that the proposed ALST map and the CT map have better chaotic performance than their corresponding standard chaotic maps.

A. *Bifurcation Diagram*

The bifurcation diagram shows the quantitative behavior of a chaotic system; it represents the relationship between the chaotic system and the control parameter. Chaotic system offers a chaotic behavior when the orbits released from an initial value can cover the whole phase space. Fig. 5.b and Fig. 6.b display the bifurcation diagrams of the newly altered Sine-Logistic-based Tent map and the Cubic-Tent map, respectively. We notice that their entire phase spaces along with their control parameters are totally covered with points. Then, the distributions of their densities are more uniform than their corresponding standard maps. In contrast, the classical chaotic maps outputs are not spread out in the entire data range, and they have a sizeable non-chaotic range. Thus, the ASLT map and the CT map ensured property makes them suitable for image encryption. To get more precision about the chaotic range, we need more tools, such as the method of Lyapunov exponent, to justify the chaotic behavior.

B. *Lyapunov Exponent*

Lyapunov Exponent (LE) represents an important tool to test the chaotic behavior. It is widely used in the world of chaos [18]. The Lyapunov exponent λ quantifies the sensitivity dependence on the initial condition of a dynamic system at a given point. The much larger is the Lyapunov exponent, the better are the chaotic proprieties [1]. As is well known, for a dynamical system, a positive

Lyapunov exponent means chaotic behavior occurs in the dynamical system [10]. For a non-linear one-dimensional discrete chaotic map f, its Lyapunov exponent is given by:

$$\lambda = \lim_{n \to +\infty} \frac{1}{n} \sum_{i=0}^{n-1} \ln|f_r'(x_i)|, \quad (7)$$

Lyapunov exponents represent the strength of the sensitivity to the initial conditions. where n is the iteration number and r is the control parameter. Fig. 7 and Fig. 8 illustrated the Lyapunov exponents, with the variation of the parameter r, of the proposed maps (ALST and CT) and the standard maps. The LE of ALST and CT maps is larger than the Logistic, Tent, Sine, and Cubic maps. We notice that the maximum LE of the proposed ALST and CT maps are more significant than their corresponding standard maps with values 0.6995 and 1.0373, respectively (see Table I). The LE values of the enhanced maps are always positive in the entire range of the parameter settings $r \in [0,4]$ except for some points of the CT map. These results indicate that our chaotic compound maps exhibit a wider chaotic range and better chaotic performance that provides a high security level.

TABLE I: MAXIMUM LE AND MEAN SHANNON ENTROPY OF DIFFERENT CHAOTIC MAPS

Chaotic maps	Maximum LE	Mean SE
Logistic map	0.6930	0.9222
Tent map	0.6931	2.8827
Sine map	0.6850	1.1066
Cubic map	1.0980	1.3591
ASLT map	**0.6995**	**7.9158**
Cubic-Tent map	**1.0373**	**7.7239**

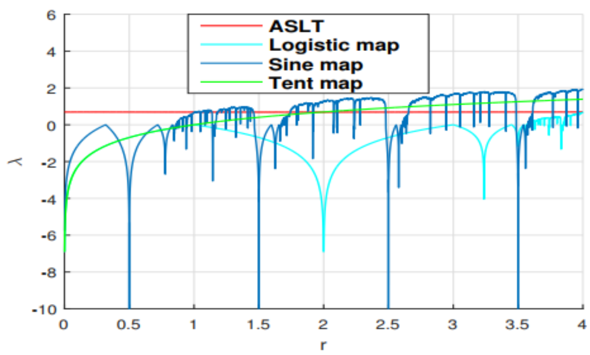


Fig. 7. Lyapunov Exponents of standards 1D chaotic systems vs the proposed ASLT map.

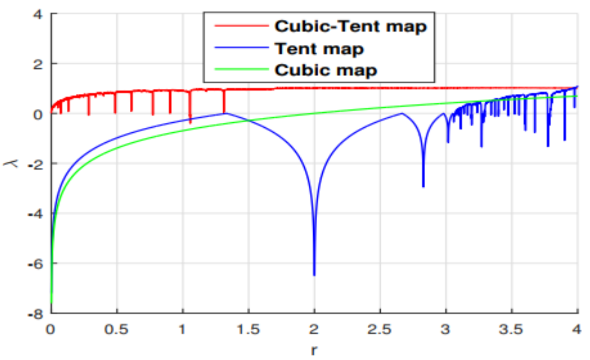


Fig. 8. Lyapunov Exponents of standards 1D chaotic systems vs the proposed CT map.

C. *Sensitivity of New Maps*

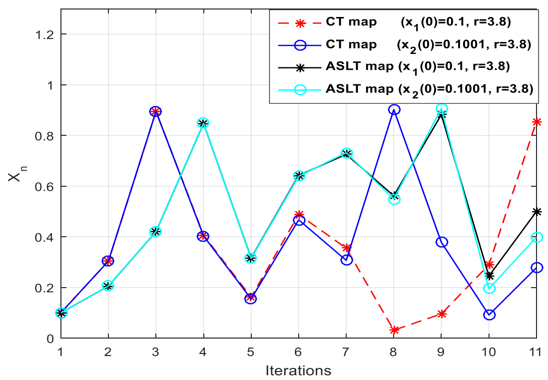
To measure the sensitivity of the new combined maps to the initial value and control parameter, we apply a tiny change to the initial value and generate two trajectories with the same control parameter. Then, we apply a tiny change to the control parameter and generate two trajectories with the same initial value, respectively. Figure 9.a shows four orbits X_n with fixed control parameter and a very close initial values $x_1(0) = 0.1$ and $x_2(0) = 0.1001$ of the CT map and ASLT map, respectively. Figure 9.b presents four orbits of X_n with fixed initial values and a very close control parameter $r_1 = 3.8$ and $r_2 = 3.8001$. We can see from Fig. 9 and Table II that the orbits of the ASLT map follow different ways after eight iterations when the initial condition changes and ten iterations when the control parameter changes. The orbits of the CT map follow different ways after three iterations and ten iterations with the changes of the initial condition and the control parameter values, respectively, as shown in Table III. These results show the high sensitivity of the proposed combined maps next to the initial condition and control parameter. The initial sensitivity results reflect the higher randomness of the proposed ASLT and CT maps.

TABLE II: SENSITIVITY ANALYSIS OF ASLT MAP

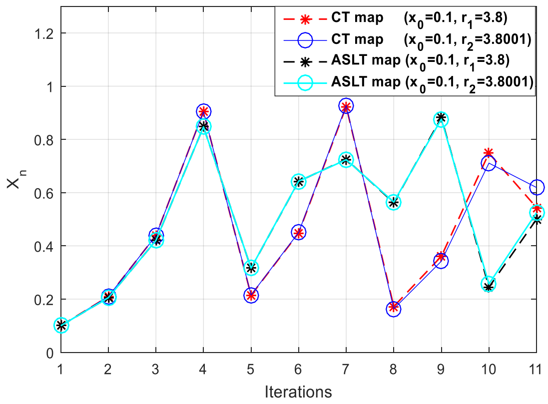
Iteration n	$x_1 = 0.1$	$x_2 = 0.1001$	$r_1 = 3.8$	$r_2 = 3.8001$
1	0.10	0.10	0.10	0.10
2	0.21	0.21	0.21	0.21
3	0.42	0.42	0.42	0.42
4	0.85	0.85	0.85	0.85
5	0.31	0.31	0.32	0.32
6	0.64	0.64	0.64	0.64
7	0.73	0.73	0.73	0.73
8	**0.56**	**0.55**	0.56	0.56
9	0.88	0.90	0.88	0.88
10	0.24	0.19	**0.24**	**0.25**

TABLE III: SENSITIVITY ANALYSIS OF CUBIC-TENT MAP

Iteration n	$x_1 = 0.1$	$x_2 = 0.1001$	$r_1 = 3.8$	$r_2 = 3.8001$
1	0.10	0.10	0.10	0.10
2	0.30	0.30	0.30	0.30
3	**0.89**	**0.90**	0.90	0.90
4	0.41	0.40	0.41	0.41
5	0.16	0.15	0.16	0.16
6	0.49	0.47	0.49	0.49
7	0.36	0.31	0.36	0.36
8	0.03	0.90	0.03	0.03
9	0.10	0.38	0.10	0.10
10	0.29	0.09	**0.29**	**0.30**



(a)



(b)

Fig. 9. The sensitivity of ASLT an CT maps to (a) changes of the initial value x_0 (b) changes of control parameter r.

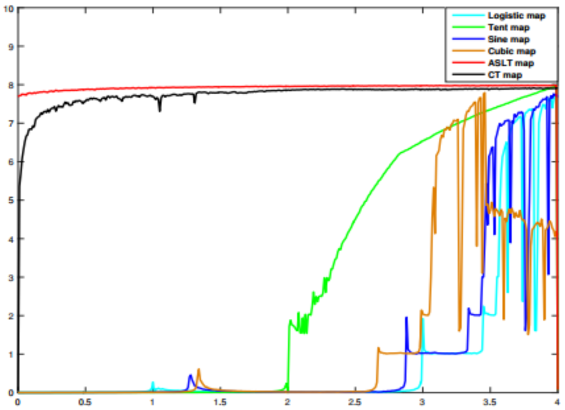


Fig. 10. Shannon Entropy of the proposed maps and their corresponding classical maps.

D. Shannon Entropy

The Shannon Entropy (SE) is used to measure the randomness of a sequence [16]. We calculate the SE for each control parameter $r \in [0,4]$ f chaotic maps for 10000-time series to test the randomness of the output sequences of different chaotic maps. Fig. 10 shows the Shannon entropy values of the ASLT and CT maps; proposed maps present much larger entropy values than classical maps. ASLT and CT maps Shannon entropies are very close to 8 when $r \geq 1.5$. Moreover, these maps have a large SE in the entire parameter interval. The obtained mean SE values, shown in Table I, prove the random distribution of the sequences generated by the proposed maps with SE ≈ 8. As shown in Fig. 7 and 8, the SE curves (Red and black) of the improved maps lie above their corresponding standards maps in the entire range of r, showing great randomness property. While the classical maps have randomness in small intervals, and their SE values are much less than the proposed maps.

IV. Conclusion

This paper proposed two compound one-dimensional chaotic maps: The Altered Sine-Logistic based on a piecewise Tent map (ASLT) and the Cubic-Tent map (CT). The proposed maps are based on the nonlinear fusion operation of standards 1D chaotic maps. The chaotic behaviors of the newly proposed ASLT and CT systems were evaluated using the bifurcation diagram, Lyapunov exponent, initial sensitivity, and Shannon entropy, presenting better chaotic performance and sensitivity compared to existing 1D chaotic maps. The results show the good performances of the proposed 1D maps exhibiting more uniform distribution, an extended range of the chaotic region, more initial sensitivity, and more randomness than their corresponding standards 1D chaotic maps. Furthermore, future work will use the ASLT and CT maps to generate S-boxes for image encryption applications.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors discussed the work structure and aligned on the research scope. Ichraf Aouissaoui conducted the research and wrote the paper; Toufik Bakir analyzed the data and provided guidance until getting to the last version; Anis Sakly has reviewed the research; Smain Femmam has modified the paper organization and outline; all authors had approved the final version.

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