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Competitively coupled maps for hiding secret visual information

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HIGHLIGHTS

- Competitively maps are used for hiding digital images.
- Non-diffusive coupling results into relatively short-transients.
- Secret image is embedded into initial state far below the noise level.

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ABSTRACT

A novel digital image hiding scheme based on competitively coupled maps is presented in this paper. Self-organizing patterns produced by an array of non-diffusively coupled nonlinear maps are exploited to conceal the secret. The secret image is represented in the form of a dot-skeleton representation and is embedded into a spatially homogeneous initial state far below the noise level. Self-organizing patterns leak the secret image at a predefined set of system parameters. Computational experiments are used to demonstrate the effectiveness and the security of the proposed image hiding scheme.

1. Introduction

The understanding of evolution of spatial patterns in simple systems remains an active research area. One of the classical models of irregular spatiotemporal patterns emerging dynamically from a spatially homogeneous initial state comprises a simple reaction–diffusion system with finite amplitude perturbations [1]. Small perturbations of initial states play a central role in the initiation of pattern formation process, whereas spontaneous self-organization yields patterns in a purposeful manner without external stimulation [2]. The diffusion of the competing species (under suitable conditions) can drive symmetry breaking in the initial homogeneous configuration [3]. Typically, situation-dependent necessary conditions must be enforced in order to ensure the emergence of spatial patterns from homogeneous initial conditions [4].

It is well known that spatial self-organizing patterns can be effectively used for hiding secret visual images. A digital fingerprint image is used as the initial condition for the evolution of a pattern in a model of reaction–diffusion cellular automata [5]. A secure steganographic communication algorithm based on patterns evolving in a Beddington–de Angelis-type predator–prey model with self- and cross-diffusion is proposed in Ref. [6]. Self-organizing patterns induced by complex interactions between competing individuals and described by evolutionary spatial 2×2 games are exploited for hiding and transmitting secret visual information in Ref. [7]. It is natural to expect that other nonlinear models of self-organizing systems could be also applicable for hiding secret visual images.

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The main objective of this paper is to seek such a nonlinear self-organizing system which would enable to construct a relatively simple but computationally effective visual communication algorithm. At least 10 000 time forward iterations are required for the reaction–diffusion model in Ref. [6] to exhibit an interpretable pattern. The inversion of a single pixel in the dichotomous random image of initial conditions does not result into any changes in the difference image in the communication algorithm proposed in Ref. [7]. This fact is based on the property of evolutionary spatial 2×2 games where the strategy of a single individual does not determine the resulting strategy of the whole population.

An effective application of a communication algorithm based on self-organizing patterns needs to satisfy several important requirements. First of all, this algorithm should be steganographically secure. Image steganography is the science of concealing secret images within other digital cover images [8]. The advantage of steganography, over cryptography alone, is that steganography can be said to protect both messages and communicating parties, whereas cryptography protects only the contents of a message [9]. Secondly, the secret visual information should be encoded in the random image of the initial conditions by using slight modifications of only several individual pixels; all modifications should be lower than the noise level of the initial conditions. Finally, the communication algorithm should be computationally effective—the number of time forward steps used for the development of self-organizing patterns should be small. Clearly, all existing communication algorithms based on self-organizing patterns do not satisfy all three requirements. The algorithm in Ref. [5] is not steganographically secure because distinct visual patterns are not hidden in cover images. Visual patterns can draw attention from eavesdroppers and thus are prone to being thoroughly analyzed and uncovered (in other words the principles of steganography fail to hold). The technique in Ref. [6] requires a large number of time forward steps and is not computationally effective; the method in Ref. [7] requires the modification of large blocks of pixels in the random image of initial conditions.

This paper is organized as follows. The model of the system is presented in Section 2; the communication scheme is presented in Section 3; the sensitivity of the scheme to the perturbation of the systems parameters is discussed in Section 4; concluding remarks are given in the final section.

2. The model of the system

Let us consider a one-dimensional unimodal mapping in the form $f(x) = x \cdot F(x)$ where $F : \mathbb{R} \to \mathbb{R}$ is a smooth mapping. We will use $F(x) = \lambda(1 + x^b)$ named after Maynard Smith [10] where parameters λ and b are positive constants.

A two-dimensional generalization of this mapping with the introduction of the competitive aspect to the model, gives the time evolution of a particular state $x(t)$ at time t on a rectangular domain $[1; L_x] \times [1; L_y]$:

$$x_{i,j}(t+1) = x_{i,j}(t) \cdot F[x_{i,j}(t) + \alpha \cdot \Sigma_{i,j}(t)] \tag{1}$$

where

$$\Sigma_{i,j}(t) = \sum_{\substack{p,q \in \{-1,0,1\} \\ (p,q) \neq (0,0)}} x_{k,l}(t), \qquad k = \operatorname{mod}(i+p-1, L_x) + 1;\ l = \operatorname{mod}\left(j+q-1, L_y\right) + 1 \tag{2}$$

is the sum of adjacent elements in the 8-element Moore neighborhood of the element $x_{i,j}(t)$; α is a nonnegative parameter that represents the strength of the competitive interaction between neighboring elements. Note that the local site dynamics are coupled through a competitive, rather than diffusive, interaction. 2D periodic boundary conditions are assumed; L_x and L_y define the number of elements in the rectangular domain. Note that every element $x_{i,j}$ represents a single pixel of a digital image.

Competitively coupled maps are based on interactions between discrete neighboring nodes. These interactions are usually interpreted as the competition from the physical (or biological) point of view. In terms of steganography, it is always important to take into account algorithmic aspects of the evolutionary model—such as feasibility, computational efficiency and complexity, memory and time requirements. A large variety of different evolutionary models exhibiting interesting behavioral aspects does exist. However, competitively coupled maps are relatively simple yet robust and computationally effective models capable of producing stationary patterns from homogeneous initial configurations—and therefore are well suited for the considered steganographic application. Moreover, competitively coupled maps presented in Ref. [10] do produce complex spatial patterns even when the dynamics at each node is trivial (the local dynamics of an isolated node does exhibit a stable fixed point). This is in stark contrast to conventional diffusively coupled map lattices where trivial dynamics of a node can only result in a spatially homogeneous state [11–13].

2.1. Initial conditions

Initial states of all elements are set as randomly distributed numbers over the interval $[0, 1]$. The chaotic logistic map [14] could be used for the efficient generation of these states—communicating parties can share only the initial condition of the logistic map instead of sharing initial states of all elements in the domain. Iterated values of the logistic map

$$a_{i+1} = 4a_i(1 - a_i) \tag{3}$$